ESEIAAT

Titulació:

MÀSTER EN GESTIÓ D'EMPRESES DE TECNOLOGIA I D'ENGINYERIA (MEM)

Alumne:

JOSEP ORIOL RIBAS SÁNCHEZ

Enunciat TFM:

DISSENY I MESURA D'ELÈCTRODES TÈXTILS PER APLICACIONS MÈDIQUES I DE L'ESPORT

Director del TFM:

IGNACIO GIL GALI

Convocatòria de lliurament del TFM:

Quadrimestre Tardor 2019-2020

UNIVERSITAT POLITÈCNICA DE CATALUNYA

ESEIAAT

DISSENY I MESURA D'ELÈCTRODES TÈXTILS PER APLICACIONS MÈDIQUES I DE L'ESPORT

Author:

Josep Oriol Ribas Sánchez

Supervisor:

Ignacio Gil Gali

Quadrimestre Tardor 2019-2020

Abstract

Achieving constant monitoring of muscles and organs would be a huge change for hospitalized or chronic patients and athletes. However, today's technology is not able to provide the best optimal solution in terms of performance and comfort. Conventional disposable AgCl electrodes used for clinical bio-signal measurements are technology limited due to their inconvenience and short application time. That is the reason why the study of textile electrodes has been proliferating in recent years. The most appropriate solution would be to incorporate biosensors into daily and unipersonal clothing. In this thesis, the study focuses on the design, manufacturing and test of embroidered textile electrodes. The dimensions and materials will be the same for all of them and only geometry and embroidery characteristics will vary.

As a result of the realization of this thesis a new embroidering and measurement methodology has been set up. On one hand, a wax coating is applied to the conductive thread which facilitates and speeds up the embroidery process. In addition, the results obtained are even better compared with non-coated conductive threads. It is therefore advisable to use it in future studies. On the other hand, it can be stated that the measurement procedure is free of human error in a high percentage.

Compared with recent other studies and projects the results obtained are better in terms of resistance. And most important, as some new methodologies or procedures have been implemented, accuracy and repeatability of the embroidering process and reliability of the measurements have experienced a quality leap.

Resum

Assolir una monitorització constant dels músculs i els suposaria un gran canvi per a pacients hospitalitzats o crònics i esportistes. Tot i això, la tecnologia d'avui en dia no és capaç de proporcionar una solució òptima en termes de rendiment i confort. Els elèctrodes AgCl convencionals d'un sol ús utilitzats per a mesures clíniques de bio-senyals resultant ser una tecnologia limitada degut a la seva poca comoditat d'ús i curt temps d'aplicació. Aquesta és la raó per la qual l'estudi dels elèctrodes tèxtils ha proliferat els darrers anys. La solució més adequada seria incorporar biosensors a la roba diària i unipersonal. En aquesta tesi, l'estudi es centra en el disseny, fabricació i mesura d'elèctrodes tèxtils brodats. Les dimensions i els materials seran els mateixos per a tots ells i només variaran les característiques de geometria i brodat.

Com a resultat de la realització d'aquesta tesi, s'ha establert una nova metodologia de brodat i mesura. D'una banda, s'aplica un recobriment de cera al fil conductor que facilita i accelera el procés de brodat. A més a més, els resultats obtinguts són encara millors en comparació amb fils conductors no recoberts. Per tant, és recomanable utilitzar-lo en futurs estudis. D'altra banda, es pot afirmar que el procediment de mesura gaudeix d'una reducció pel que fa percentatge d'error humà.

Comparat amb altres estudis i projectes recents, els resultats obtinguts són millors en termes de resistència. I el més important, ja que s'han implementat algunes metodologies o procediments nous, la precisió i la repetibilitat del procés de brodat i la fiabilitat de les mesures han experimentat un salt de qualitat.

CONTENTS

List of Figures

List of Tables

1. Introduction

1.1. Objectives

The main objective of this thesis is to study, design and measure embroidered textile electrodes considering geometry, weaving technique and stitch parameters which all combined contribute to the best set of electronical and electric properties of a dry textile electrode considering always its cost. Electrodes that in the future will allow the measurement of skin biopotentials and reach a constant monitoring of muscles and organs of patients or athletes.

As this is a cutting-edge technology there is still an uncertainty about how exactly works and how the electricity flows through the electrode. As it is for the procedure to follow.

The creation of an embroidery and specially a step to step measurement method is important to set up the same bottom line for all the studies to come. This will be a secondary objective but not less important. The main reasons are to be able to minimize human errors and increase repeatability and reliability as well as obtain better electrodes that has been obtained so far. This measurement process will be based basically on the assessment of the impedance which depends on two factors; resistance and reactance.

1.2. Scope

A state of the art about future wearables is presented. It is briefly explained which was the necessity that drive the conception and deep study of textile embroidered sensors. Some potential applications and the firsts studies are listed, basically in healthcare and sports fields.

At this point, present or traditional technologies and the physics behind this technology are detailed. Even though, both textiles embroidered and current sensors share the same basis, there are some factors to consider that tilt the balance in favour of the use of this new trend. On the other hand, as a new know how, downsides about the technology exists. There are some factors to point out and continue working on them to be able to obtain optimized sensors.

To continue, and from all the knowledge gathered, there are presented the main ideas and considerations taken to realise the thesis.

The following part is devoted to the study of textiles embroidered sensors itself. The study is based on the building of samples with different processes and weaving techniques. At the same time, the optimization of the measurement process is being stablished. Afterwards, samples are tested. The extracted results are analysed in order to confirm which sensor depending on the variables did obtain better results considering always its price.

1.3. Requirements

This thesis is based specially on the previous one held on the UPC [1]. They embroidered some electrodes with different embroidering characteristics and sizes. Afterwards wet and dry resistance measurements were held. Results obtained are considered as bottom line and ideas to build up on. Those are the followings:

- Higher densities of conductive thread enhanced higher performances in the project. Weave and satin will be the only weaving techniques used.
- From their results, this thesis will characterize resistance only under dry conditions as wet studies displayed misunderstanding results.
- The best resistance values where obtained in 4 x 3,3 = 13,2 cm^2 electrodes.
- The Singer Futura XL – 550 and its integrated software will be the sewing machine to use. The software to design the electrode will be EasyDesign EX.
- As conductive thread the Silver-Plated Nylon 66 117/17 dtex two-ply will be used. And for the bobbin will be a commercial no-conductive polyester thread.
- Fabric to use will be the same as well.

2. State of the Art

2.1. Introduction

Cities and homes, industry, agriculture, energy, transport and even wearables, internet of things (IoT) is widely spread all over the world nowadays. Even though its definition has evolved during the past years due to the convergence of multiple technologies its basis remains the same, ease and improve the standard of living as human beings. Currently we are able to keep in touch with friends and relatives most of the time and we are even capable to do it instantly. We have gone far enough to connect people between each other, however, there is still a lot to do to connect with ourselves, to know about our body, including organs, muscles or bones.

Through some phone apps anyone can check their physical activity of the day such as walking and running distance, number of steps, flights climbed, running pace, path followed and so on. Besides, there are wearable devices, where skin contact is necessary (basically watches or bracelets), with which oneself can track down its heart rate or sleeping activity. This muscle monitoring is not only useful as a daily use device but also to prevent injuries, morbidity and even mortality.

2.1.1. Motivation

It would be a real-life change for a patient with a long term chronic and degenerative illness if he is equipped with a set of those wearable sensors as their activity, movement and well-being can be monitored continuously and remotely. Those devices would be able to take relatively simple measures and use signal processing and multi-parameter analysis to derive the physiological parameters of interest to provide an early detection of pathological signs and improving the curative rate of diseases without intervening in the patient's daily life [2]. Besides the healthcare point of view, it would be a cutting-edge technology on the sports field as well. An athlete equipped with this technology could monitor as well their muscle activity [3] They could store real data of their sessions related with their muscle's behaviour under certain conditions. Study and analyse this data afterwards would permit to train or focalise some exercises in a very specific matter. The quality of trainings, rehabs or specific exercises would be boosted exponentially.

2.2. Conception

As we are talking about sensors that should be worn most of the day and keep in contact with the user's skin, clothing come up in our mind. Clothes are individual's possessions and are used daily in our routine. The original purpose of clothing was to protect the individuals from the weather, and it did not change that much. Actually, as it said on the first section, everything that surround human beings' daily life has exponentially evolved technology to increase living standard but not clothes. General clothing, did not change that much besides increasing comfort, however, now it turns out to be the perfect holder for these wearable sensors. Clothes could also get involved in this technological era. So, the technological drive is to make them intelligent integrating sensors and electronics but always maintaining its advantages such as reliability, comfort and washing resistance.

2.2.1. Firsts attempts

To integrate electronics and sensor into clothing embroidery is the right method as it is based in adding material on an already existing fabric. Due to the advances in miniaturization of electronics through weaving and knitting techniques researchers have already added fabric antennae and integration electronics into textiles [4][5].

Specifically, some of the example are the followings: integration of electrodes into jogging leggings to monitor leg muscle activity and fatigue during exercise [6]; done as well in a ventilatory threshold detection during incremental running in [7]; to monitor job-related ergonomics through muscles status in working people involved in potentially unhealthy postures; or asses comfort in jobs involving precise tasks with special or heavy tools, long hours, unusual postures leading to difficult lifestyle [8,9].

2.3. Present Technology

2.3.1. Theoretical background

All living cells are surrounded by ion selectively permeable membranes and may actively let them through resulting into a membrane biopotential (potentials in an organic system). CL^-, Ca^+, and Na^+ ions are responsible to transport charges through a human body. A certain threshold voltage can depolarize nerve cells and muscle fibres when activated. The result is the propagation of a depolarization wave along the nerve and muscle fibre [10]. The physiological response to this wave circulating through the muscle is a quick combination of its contraction and relaxation, a "twitch". Since all muscle fibres do not twitch simultaneously, the overall observed potential over a muscle is the random summation of multiple single fibre action potentials. This random signal is conducted to the surface of the skin by means of volume conduction. Electrodes are placed on the skin in order to record this muscle biopotentials. In order to measure them, the ions currents have to be changed to electron currents in the electrode.

Currently, there are many commercial electrodes available. The most commonly used ones are the disposable wet electrodes for medical clinics based on Ag/AgCl with the combination of a gel layer as electrolyte which improve ions currents. They are widely spread in different clinical applications using alternating current (AC) at various frequencies depending on which different bio-electric event they are to detect. Those are, for example, electrocardiography (ECG), electroencephalography (EEG) and electromyography (EMG); transcutaneous electrical nerve stimulation (TENS); and also, iontophoresis and bioelectrical impedance analyses (BIA) [11-12].

The ECG is a specifically widely studied biosignal which describes the electric action of the heart. The ECG consists of three main parts: QRS-complex, P-wave, and T-wave that are used to measure those ions currents on the human body, the biopotentials [13]. From those analyses others more specialised are used.

Non-invasive BIA are based on the characterization of a surface electromyography (sEMG). Composed by an electronic system composed itself of differential amplifiers [15,16] and non-invasive biopotential surface electrodes. BIA enhances the monitoring of muscle gap and injuries [14,17-19], fractures [20], biotissue abnormalities [21-24], diseases [25], inflammation [26] and wounds [27,28]. In all these characterizations, single frequency BIA (sfBIA) measurements is used commonly at a frequency of 50kHz. That is why there are already several commercial options.

2.3.2. Traditional electrodes

Commercial electrodes are divided in two different groups; wet and dry. The traditional electrodes however are the wet ones, they are the most spread and used frequently in medical clinical [29,30]. There are some considerations to take into account about wet traditional electrodes that finally drive the conception of the dry textile embroidered electrodes.

First and foremost, they are only one-time use, they are disposable. This represents a high cost not only monetary but ecological as well. There are also technical downsides. As the outer layer of the skin has a dry dielectric layer, called the stratum corneum, it causes reduction of the transfer mechanism from ions to electrons. It is mandatory then to prepare the skin to acquire results. The use of an electrolyte gel that moisturizes the skin and makes it highly ion conductive is necessary. Sometimes it is even needed to shave the application area. Besides, an adhesive layer to improve stickiness is used on the electrode and it can cause irritation or even allergic reactions to the patient or user. Moreover, it is not suitable for long-term monitoring as longer the time of study gets, higher probability that its adhesive layer dries and becomes unsticking, thus the skin contact percentage may decrease and wrong results would be obtained. Another issue is the correct placement of the electrodes on the body, some knowledge is needed. So, the user cannot place it correctly at first instance. There are also certain issues with the electrolyte gel. If the application time is too long it could dry and if an excess is applied it could cause short circuit [13,31].

For any kind of characterization mentioned in the previous section it is vital to obtain a clear biosignal, undistorted and ideally artefact-free. The efficacy of the measurements is directly related with the electrode configuration and its proper contact with the skin. Thus, wet traditional electrodes are not the best suited option for this kind of measurements. Preparation time is considerable and user comfort drawbacks are too many regarding the accuracy of the results obtained. Using dry electrodes instead, reaching a good contact area without any comfort troubles for the user is affordable. A dry electrode is an electrode that it does not use a wet gel layer as electrolyte. Some of them are membranes [32-44], drying paste membranes [45] or tattoos [46,47]. Textiles are also one of the main dry electrodes and the main topic of this thesis.

2.4. Textile Electrodes

Non-invasive wearables platforms are composed by two main points. An electronical acquisition system which comprises a differential amplification followed by filtering used to process and adjust the data (2 and 3 in **Figure 2.1**). And the biopotential textile electrode which is the interface between this last one and the user's skin (1 in **Figure 2.1**).

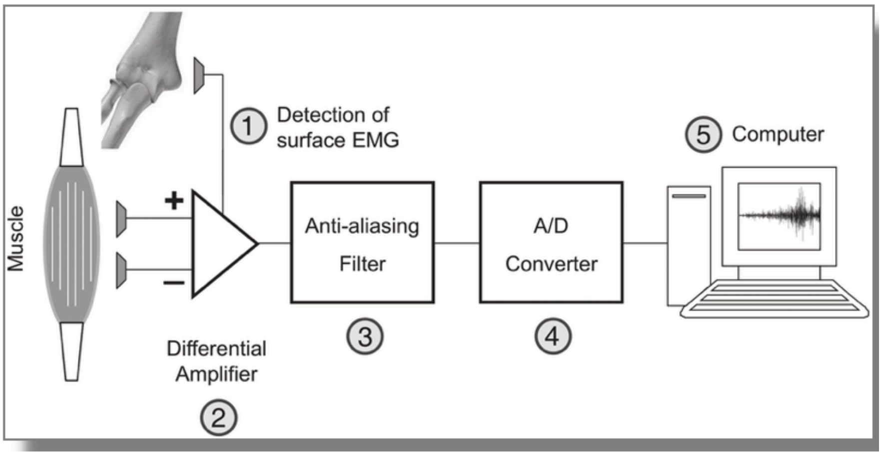


Figure 2.1. Simplified block diagram of a typical sEMG acquisition system [48]

2.4.1. Pros v Cons

Dry textile electrodes present a number of engineering challenges but they also solve some of the traditional electrodes. All the user's comfort drawbacks would be eliminated. An embroidered electrode is ergonomic and as comfortable as any clothing piece. It is as well a low-cost solution as it reusable and environmentally friendly. The correct placement would never be a problem anymore. The user would put on its clothes as usual, nevertheless, movement issues would continue to happen. Despite mismatches are the largest source of noise, it would be more manageable as the electrode could be embroidered in a tight piece of clothing reducing the probability and percentage of no-contact area. Another issue that would persists is signal noise. Once the bioelectrode is placed, it can pick up cross-talk, signals from surrounding not-studied muscles or organs. The integrated electronics would have to clear the signal as they do in a traditional electrode.

Skin-electrode interface still being considered one of the most critical points in sEMG systems. Most problems come from the skin's conductivity and polarizing impedance (Z_p) that vary from person to person and it even does for the same one based on the area or how moist and hairy it is. The impedance can even evolve in a long term based on the user's lifestyle [49].

2.4.2. Polarizing impedance (Z_p)

Electrode Z_p is the polarization of the electrode due to the charge-build-up on the electrode relative to its design, material and working frequency. Thus, it impacts directly to the stability of measurements produced by the electronic system. Some of the artefacts, as it is already said, come from cross-talking or mismatch but basically and the most important because of its dry working conception, not using an electrolyte gel triggers higher noise levels compared to those using it.

Z_p is the complex vector sum of a real part, resistance (R), and an imaginary part, reactance (X_C), relative to the frequency of the system (**eq. 1**). To calculate the total impedance, it is used the modulus of Z_p (**eq. 2**). The design and testing of dry electrodes it related to its specific frequency and therefore its medical application.

$$X_C = \sqrt{R^2 + X_C^2} \qquad \textbf{(eq. 1)}$$

$$|X_C| = \frac{1}{2\pi f C} \qquad \textbf{(eq. 2)}$$

Despite those polarizing impedance troubles, textile electrodes are one of the best solutions so far. First and foremost, from its conception idea, they can be worn all day so monitoring would be constant. Some other benefits come from the fabrication methodology thus it enhances repeatability, versatility and a wide range of design customization. Electrode and thread layout such as area, geometry, density and stitch parameters can be customized.

So then, identifying the optimum design is the key in order to pursue a configuration that enhances lower Z_p values and keep costs to a desirable level. The use of digital embroidery is adopted in an attempt to better control the design variables and reach repeatability which is not an option with handcraft.

3. Development

3.1. Materials

3.1.1. Fabric

The fabric where the electrodes are embroidered on is a green commercially purchased polyester non-woven felt of about 1mm think (**Figures 3.1, 3.2**). It has been selected considering its ionic and dielectric properties. As it is an impervious material to water it does not absorb humidity so, its electrical resistance remains unaltered in time. It was also selected due to its resistance to fraying and due to its superficial characteristics, that ease embroidering on it as it does not slip or stretch. Considering its properties just mentioned this same material is used in a 4,5 x 4 cm swatch to test the electrodes paired together in a wafer method [30].

Figure 3.1. Comercial Polyester

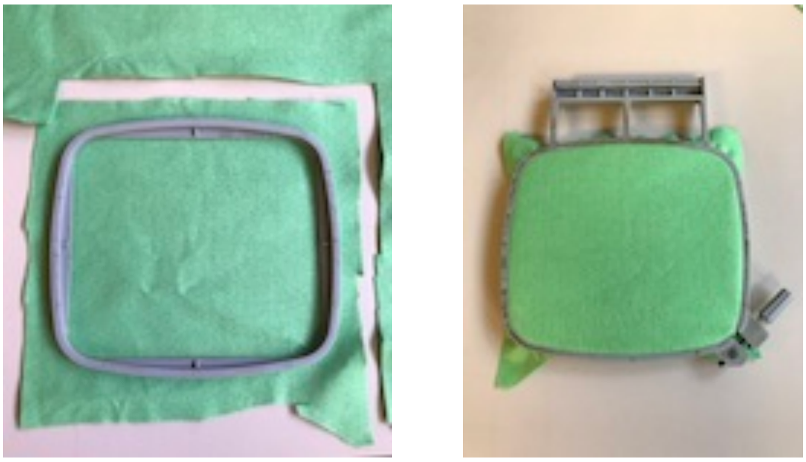


Figure 3.2. Patch to embroider on (a). Polyester final set up (b).

The polyester permittivity is measured taking the ratio of the capacitance with material between the plates versus the capacitance with free space between the plates (**Figure 3.3**). The obtained result is εr=1,336174.

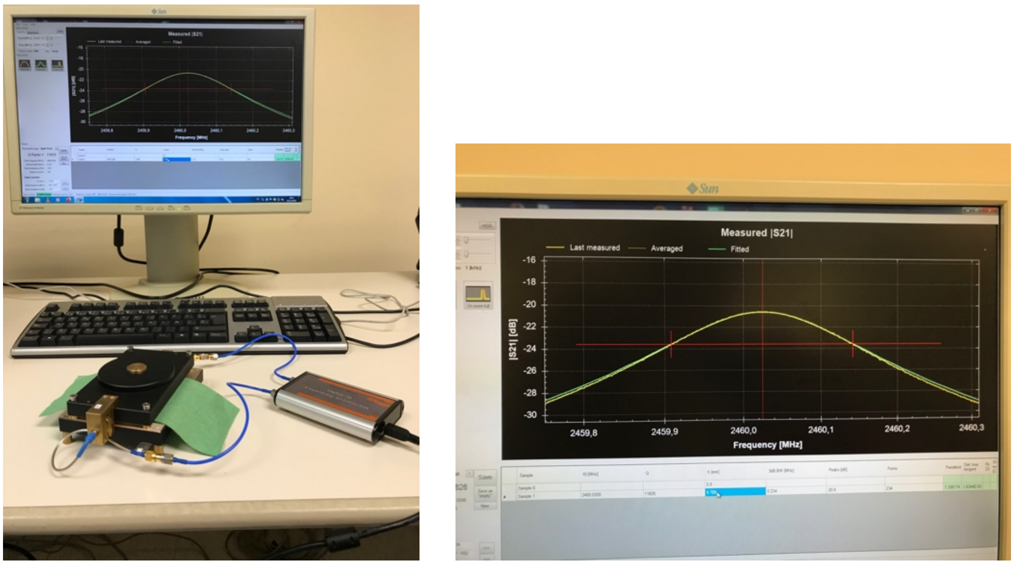


Figure 3.3. Permittivity measurement setup (a). Permittivity result (b)

3.1.2. Threads

A conductive and non-conductive polyester thread were used to produce the samples (**Figure 3.4**). Conceptually, only one side of the electrode will be in contact with the user's skin and this is the side where the conductive thread will be embroidered on. On the other side, it is embroidered a non-conductive polyester thread following the same pattern. As a result, it is achieved a reduction of the overall cost of the electrodes with no significant impact on their performance. The conductive thread adopted for this study is a Shieldex Conductive Twisted Yarn – Silver Plated Nylon 66 117/17 DTEX 2 PLY (Shieldex U.S., Palmyra, NY, United States) [50]. It was selected considering its high electrical performance and antimicrobial properties. For the bobbin, it was selected a commercial polyester non-conductive thread with a relatively close linear density to the Silver-Plated Nylon. This is an important point to consider, not only for the budget, but as it is needed to relax tensions between both threads. Balance the needle and bobbin thread's stress of the embroidery machine is key. Firsts and foremost, is a safety matter as if tensions are not balanced the needle could break and harm the user. Specially if they are looking closely to the process. Ease and speed up the embroidering are also points considered to balance tensions. As it will be detailed in following sections, a paraffin wax layer had to be applied to the conductive thread to be able to manage tensions and craft some of the electrodes.

Figure 3.4. Conductive and polyester thread (a) Polyester bobbin and tools (b)

Commercial metal snap-fasteners with a 12 mm diameter were mechanically attached to the electrodes to be able to measure the electrode's properties.

3.1.3. Holders

To stablish a repeatable and reliable measurement process, two 3D printed plastic holders where designed and crafted (**Figure 3.5**) to press the triple-layer wafer electrodes as a sandwich. The filament material used is a a biodegradable plastic made of vegetable derived sugars called PLA filament 1,75mm (F000112) from BQ.

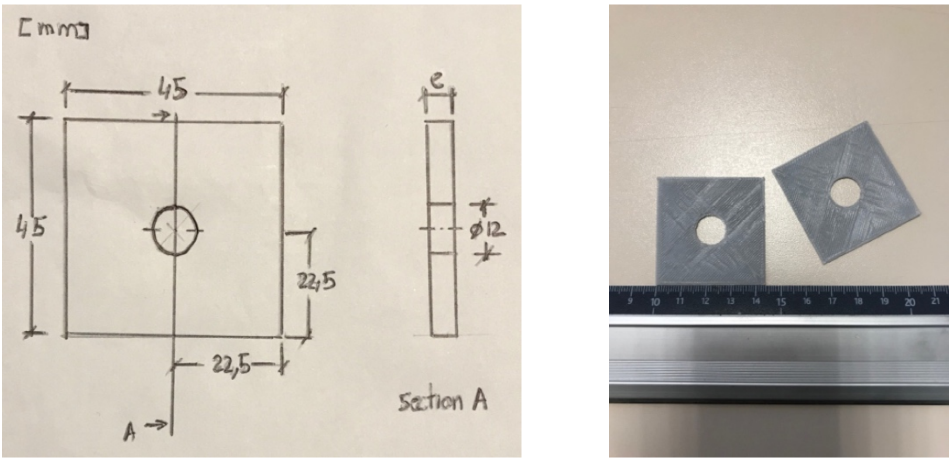


Figure 3.5. Holder's design sketch (a). Holders 3D printed (b)

The 3D printer used was the ctd prusa i3 (**Figure 3.6**) with the following settings (**Table 3.1**).

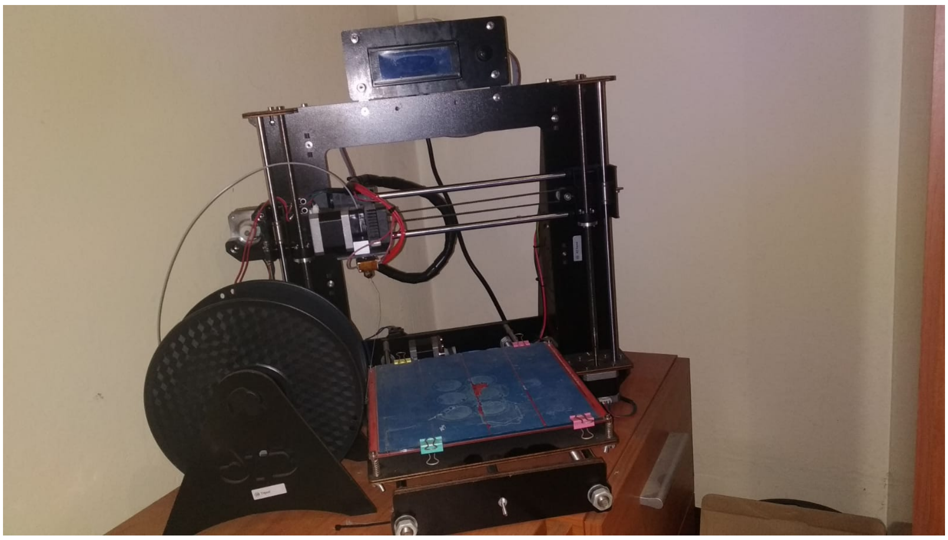


Figure 3.6. Ctd prusa i3

Layer height	0,3 mm	**Printing temperature**	205ºC
Wall thickness	0,6 mm	**Build plate temperature**	0ºC
Top/bottom thickness	1,5 mm	**Print speed**	80 mm/s
Infill density	20%	**Travel speed**	120 mm/s

Table 3.1. Printing settings

3.2. Embroidering Methodology

3.2.1. Electrodes design

The design of the electrodes was done using the embroidery software EasyDesign EX (**Figure 3.7**). The interface with the user is really simple and makes it easy to understand and work with. As a specialized software, it offers a lot of different possibilities. Afterwards, this design is exported to the Singer's Futura format and display on its software (**Figure 3.8**). Once the characteristics of the electrode are set and the embroidering process started, the user can check out how the process is going and the number of stitches left.

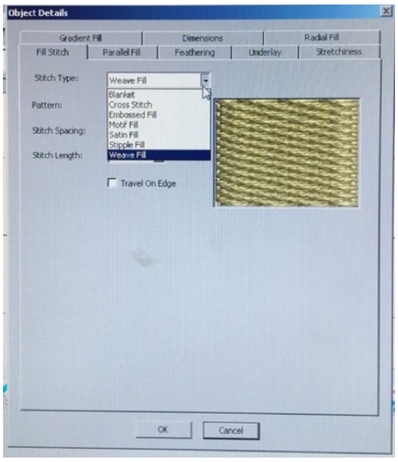


Figure 3.7. Design of the electrode

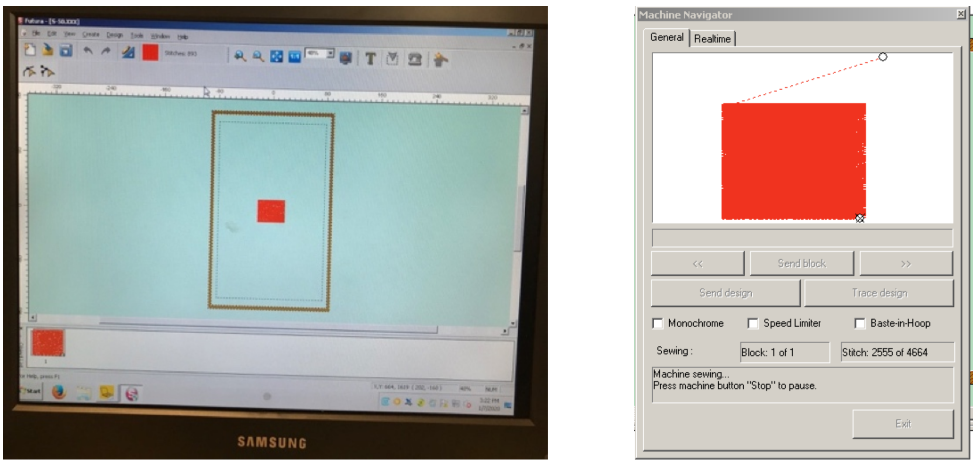


Figure 3.8. SF XL-550 software - interface (a) – running process (b)

3.2.2. Electrodes crafting

To embroider it is used the Singer Futura XL-550 embroidery machine (**Figure 3.9**) with stitch types corresponding to the ISO 4915:1991 301 standards where an identical stitch is formed on the top and the bottom of the textile [51].

Figure 3.9. Singer Futura XL-550

The following table (**Table 3.2**) represent the samples decided to produce and study. The results from [1] were taken in consideration so all the electrode's dimensions are the same (4 x 3,3 cm with a surface area of 13,2 cm^2) and only weave and satin stitch with different stitch spacing/density are studied.

Stich Type	Stitch Length [mm]	Stitch Spacing [mm] / Density [%]	Paraffin Wax [Y/N]	Code
Weave	3,5	0,8	N	W-3,5-0,8-N
Weave	3,5	0,4	N	W-3,5-0,4-N
Weave	3,5	0,2	Y/N	W-3,5-0,2-Y W-3,5-0,2-N

Weave	7	0,6	Y	W-7-0,6-Y
Weave	7	0,4	Y/N	W-7-0,4-Y W-7-0,4-N
Weave	7	0,3	Y	W-7-0,3-Y
Weave	7	0,2	Y	W-7-0,2-Y
Satin	-	50	Y	S-50-Y
Satin	-	75	Y	S-75-Y
Satin	-	100	Y	S-100-Y
Satin	-	125	Y	S-125-Y
Satin	-	150	Y	S-150-Y

Table 3.2. Samples to produce

Up to 4 electrodes were embroidered on the same fabric patch (**Figures 3.10**). Afterwards, and to be able to realize the measures they are cut with a 1mm margin.

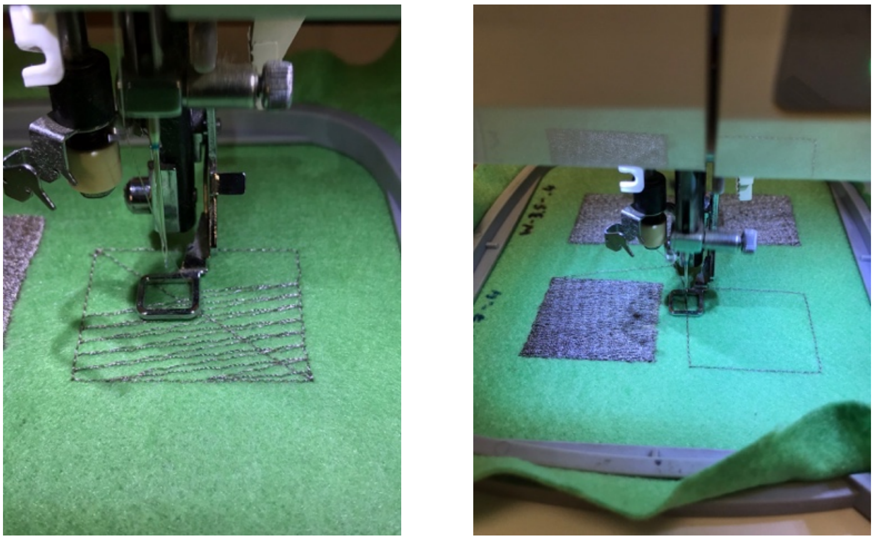


Figure 3.10. Samples embroidering process (a) and (b)

3.2.2.1. Electrode's crafting developing

The samples with lower stitch spacings were more difficult to craft. Lower stitch spacing represents a greater number of stitches for the same area and consequently longer working times. Threads breaking began to be constant after 30-45 min of sewing. Specially the electrode W-3,5-0,2, which represents around 4700 stitches and about 1 h 45 min of machine sewing straight. The problem could come from unbalanced tensions or increased working temperature.

As it has already been said, the achievement of the required tension balance was done in [1]. Although they did not push the sewing machine as much are it is done in this thesis, the conductive thread covered properly its side of the electrode. Neither the machine or the fabric seemed to work specially strained (**Figure 3.11**). The tension of the top thread was set to its maximum value and additional weight discs were stacked up with a total weight of 42,12 x 10^{-3} kg., while the tension of the bobbin was loose.

Figure 3.11. Electrode W-3,5-0,2-N

The temperature was the problem. The continuous silver-coated conductive thread friction in-between the guide plaques (**Fig. 3.12**) of the Singer Futura started to peel them and shortly breaking completely. The electrode W-3,5-0,2 which theoretically would be crafted in about 1 h 45 min finally lasts around 2h 30 min. Besides, even producing the easiest electrodes (with bigger spacings) if the machine has been working before remained hot and it turned to be really tedious to work with it as the thread broke constantly. The solution proposed was to apply a paraffin wax to the thread. At first glance, as it is a technique already used to solve breaking threads problems it is supposed that it will not affect in the thesis study. However, a comparing study in 2 equally embroidered electrodes is held to verify it and all the following electrodes are made with this conductive thread wax coated.

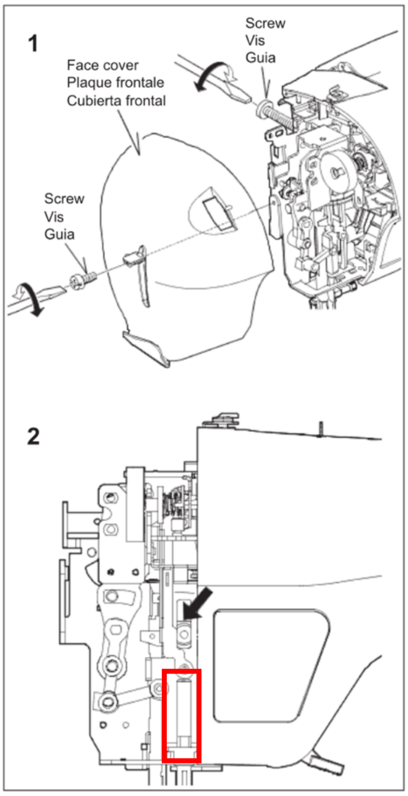


Figure 3.12. Singer Futura Cover. Detail of the guide plaques.

Other casual or random difficulties appeared sometimes while embroidering. Most of them due to the failure of the conductive stitch to be knotted with the bobbin thread or threads breaking due to imperfections. Those are easy to solve matters as moving back the needle the user can restart the embroidering where it begun. In **Figure 3.13** and **3.14** as the knotting or the breaking happened on a peripheric point it was decided to kept the process going to be able to record it. In **Figur**e **3.15** however, the bobbin thread kept on the top of the electrode for some time and it had to be removed from study.

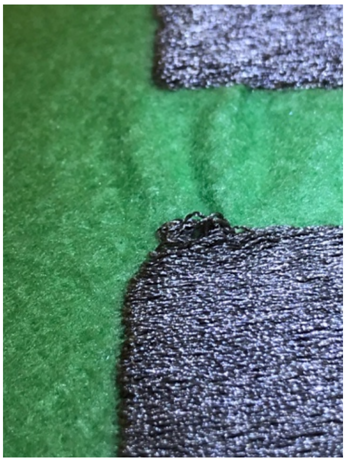


Figure 3.13. Embroidering imperfection

Figure 3.3. Embroidering imperfection 2

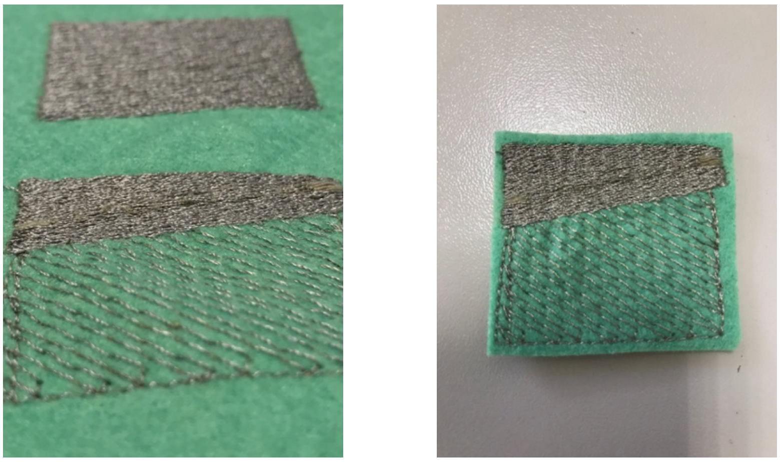


Figure 3.15. Embroidering imperfections (a) and (b)

3.2.3. Connection set up

Once the electrodes are ready a 12 mm diameter snap-fastener is attached. The purpose is to ease and reduce errors occurrence during the measurement procedure. To attach this snap-fasteners a specialised nipper (**Figure 3.16**) is used trying to position them in the middle of the electrode with the ball part on the no conductive thread and the spikes ring on the conductive side analogous to clinical electrodes. The effect of the snap-fasteners is neglected as the size through all the electrodes is consistent and it has a moderate impact on the overall electrode behaviour as the capacitance depends on geometry and size of the whole electrode being the snap component significantly much smaller than the embroidered electrode itself. Besides, the snap-fastener is needed to connect the measurement system and it has to be considered as a whole.

Figure 3.16. Snap-fasteners attachment

3.3. Measurement Methodology

For the electrode's measurement of R and X_C it was applied the wafer method. The idea is to hold somehow two electrodes equally embroidered with a swatch of the same fabric they are embroidered in in-between avoiding a snap-fastener short-circuit. The electrodes are tested in a dry environment as a result of [1] where wet environments displayed creep results. To realize the measures each electrode was connected to a voltage driven HM8118 LCR Bridge/Meter (Rohde & Schwarz, Munich, Germany) with an accuracy of 0,05% and at 50kHz.

3.3.1. Holders design

Try to standardize the measurement methodology was a secondary objective of this thesis but not less important. Until now three wooden clothespins were used to hold the triple layer wafer (**Figure 3.17**). After three minutes of stabilization the values were taken. Using this procedure, the technician must be very accurate and even then, man made errors occurrence are highly probable due to the correct contact between surfaces in the triple layer wafer. Consequently, depending on how properly were the clothespins attached the result may vary significantly.

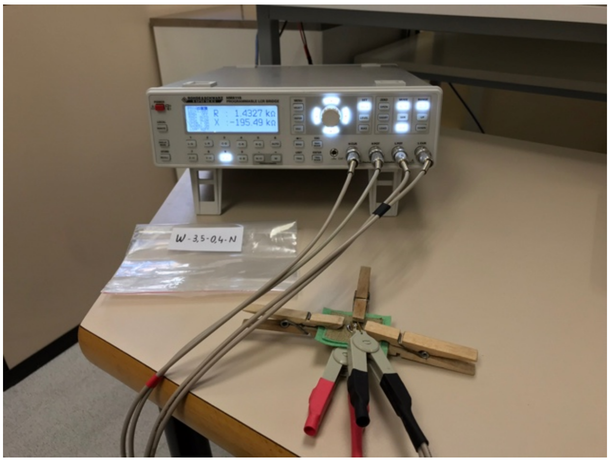


Figure 3.17. Three clothespins mesurement

In this thesis, after some failures, a solution less human dependent is provided. The objective was to find a way to make sure the contact between the triple layer wafer was proper in all the surface. In addition, a reduction of preparation time was sought as well as using three wooden clothespins and then attach properly the crocodiles from the LCR meter was really time consuming.

The first attempt was to switch to nine mini wooden clothespins (**Figure 3.18**). The aim was to increase contact area but increasing preparation time as well. Depending on how were attached these mini clothespins the results obtained could be completely different due to the metal part contact with the electrode so this option was quickly rejected.

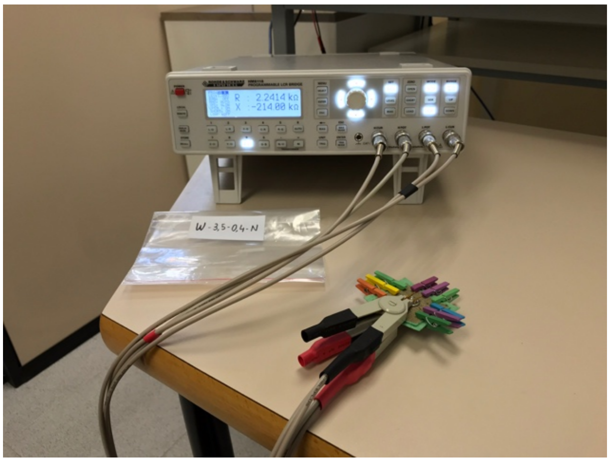


Figure 3.18. Mini clothespins measurement

Afterwards, confine the triple layer wafer in-between two plates like a sandwich was the objective. A PET plastic and wood were used (**Figure 3.19 a, 3.20 b**)**.** The PET plastic was a pretty good solution. The results obtained were quite realistic so it seemed to be a good solution. However, the pressure done by the three wooden clothespins folded the plastic plates sometimes and they did not ensure a 100% surface contact (**Figure 3.20 a**). On the other hand, with the wooden plates keep attached the LCR Meter crocodiles was impossible (even with a more optimized design, **Figure 3.19 b**) as they were too thick. Small binder clips replaced the clothespins.

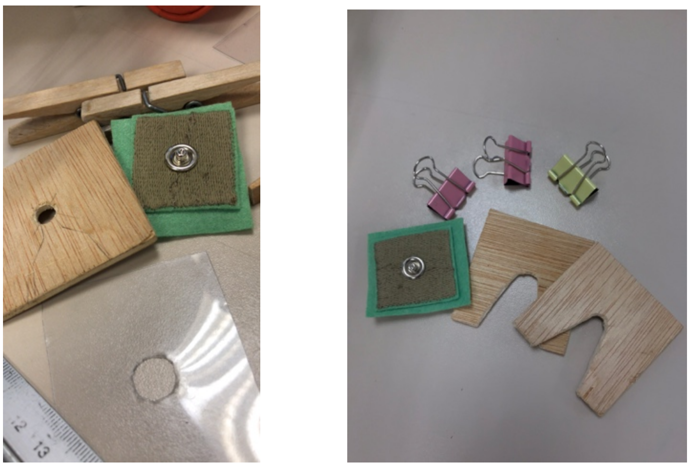
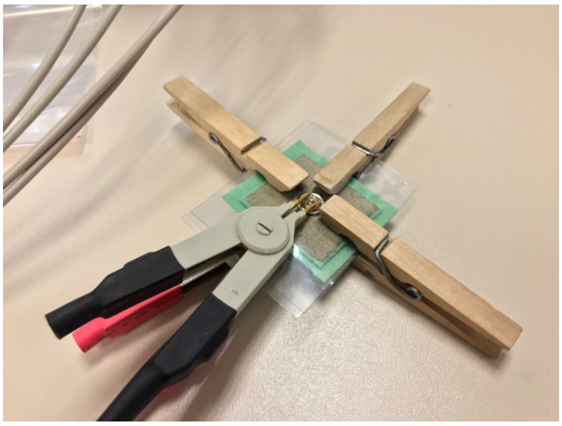


Figure 3.19. Holders – Wooden and PET plastic (a) Optimized wooden (b)



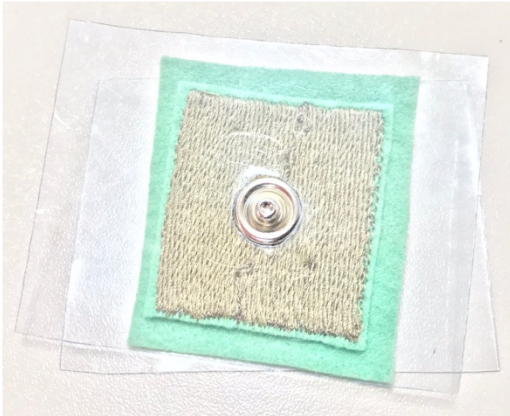


Figure 3.20. PET holder with 3 clothespins (a). Detail of PET holder (b)

Parallelly two plates with the same design of the optimized wood design and the PET plastic ones were 3d printed (**Figure 3.21**). This final solution was adopted and it provided a more solid and handy sandwich. For convenience the wooden clothespins were finally swap by big binder clips. Using them the way to attach the LCR Meter could be consistent through all the samples. It is needed to take in consideration that metal binders must not touch the electrodes as the measurement results would be incorrect (**Figure 3.22**).

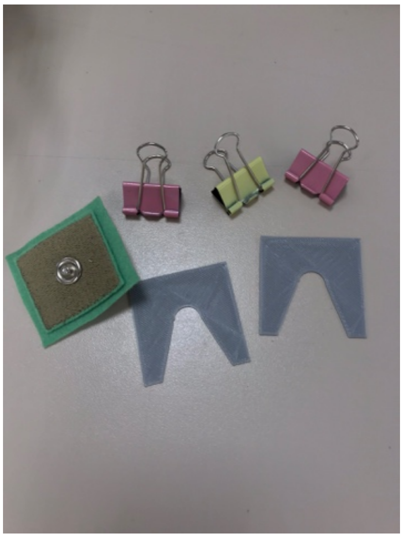


Figure 3.21. 3D printed holder – Optimized wood design (a). Final design (b)

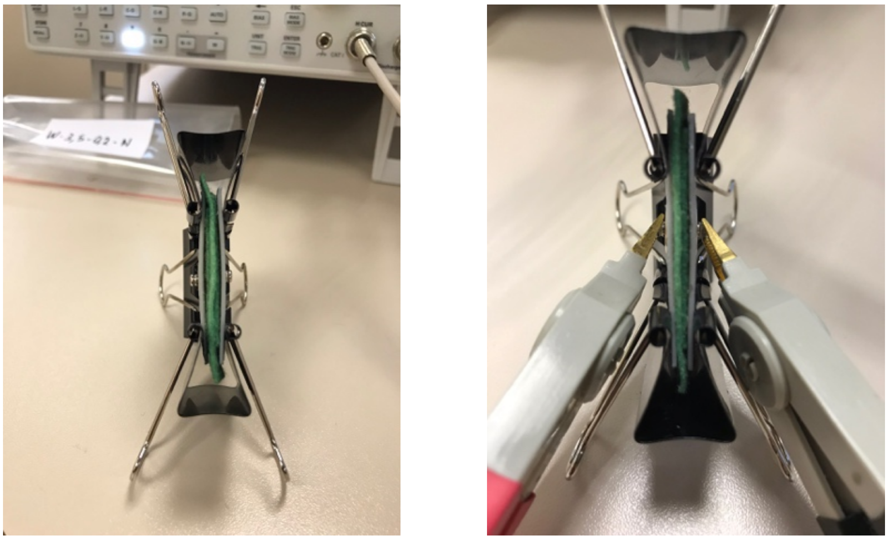


Figure 3.22. 3D printed holder setup (a). LCR Meter attachment detail (b)

3.3.2. Measurement procedure

During the first measures, in percentage it could be seen how the trend for X_c values was quite stable. However, the values of R did not really stabilize for the first minutes (**Figure 3.23** and **Table 3.3**). The main objective was to find out an electrode which characteristics minimizes Z_p. Following the **eq. 2**, if reactance remains stable the most important point is to reduce the resistance in our electrodes. So, it was decided to focus the study on resistance (R) measures. As it is a developing technology the flow through the electrode is still unknown as it is a really tight network of conductive thread. The current may not follow a straight path but jumping from thread to thread as it was tangled. This phenomenon makes the stabilization longer and quite uncertain. Experimentally after about 15 - 20 min the values did stabilize and were taken. The procedure will be to take R values 5 times every 5 seconds at minutes 5, 10, 15 and 20. Additionally, conceptually the biosensor would be in constant contact with the user’s skin so taking values after a longer stabilization time would reflect the possible real results more accurately.

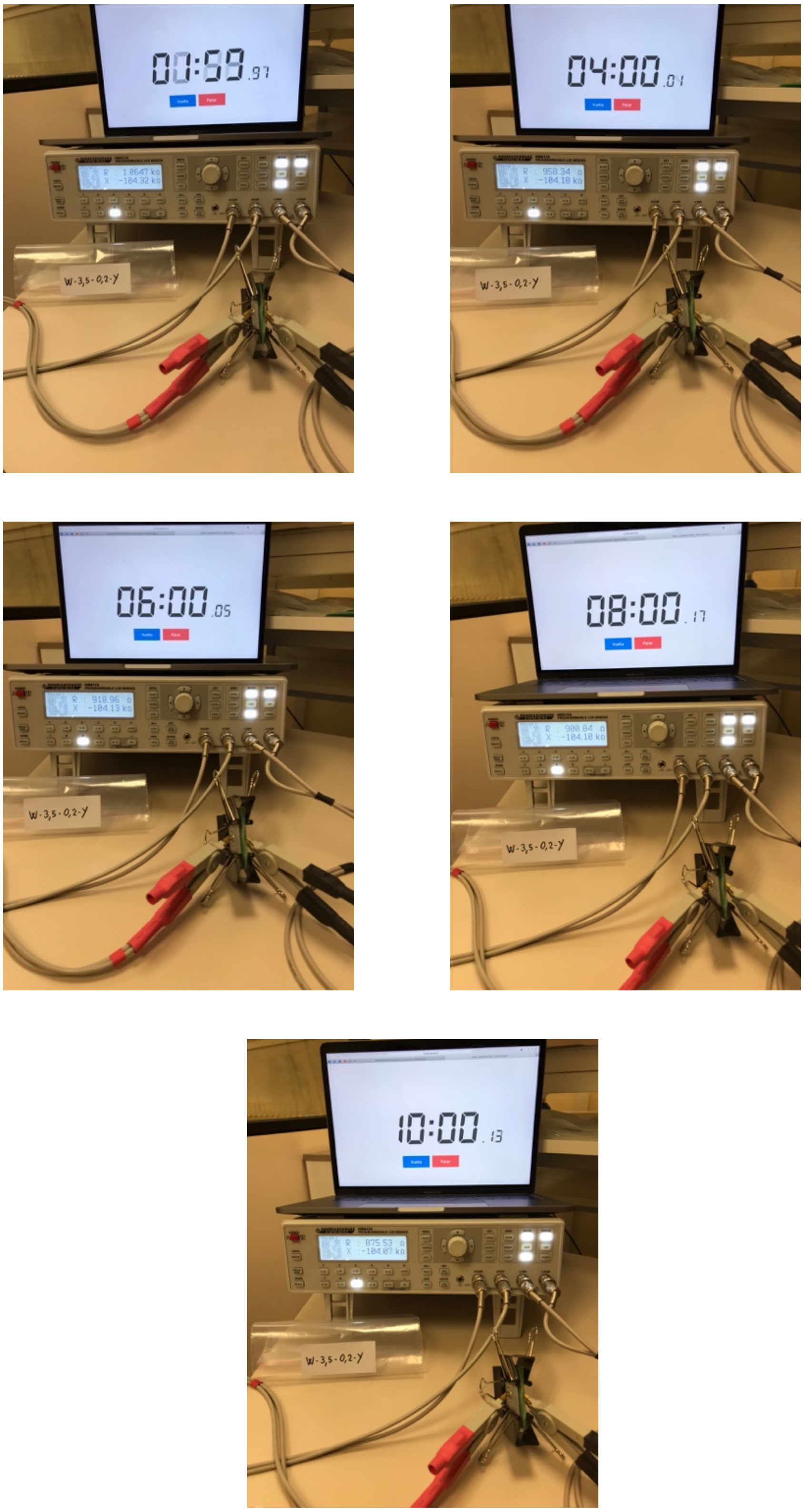


Figure 3.23. W-3,5-0,2-Y – 10 min measurements

Time [min]	R [Ω]	ΔR [%] (2 min)	ΔR [%] (previous measure)	X_c [Ω]	ΔX_c [%]
2	1064,7	1	-	-104320	1
4	958,3	10,0	10,0	-104180	0,13
6	919	15,2	4,1	-104130	0,18
8	900,8	17,8	2,0	-104100	0,21
10	875,5	21,0	2,8	-104070	0,24

Table 3.3. W-3,5-0,3-Y – Differences in first 10 min measures

As it can be seen, after 10 min of current flowing through the electrode, the values of resistance (R) did not stabilize at all. After 10 min exposition there is an incredibly 21% reduction of the resistance respect the value taken at min 2. However, the longer the measurement goes, the variation tend to be smaller.

On the other hand, the values of reactance (X_c) keep almost the same.

4. Results

Some different studies were held during this thesis. On the appendix all results and tables can be found.

Waxing the conductive thread resulted to be crucial to gain agility and speed while embroidering, so the first point was to know if it did affect or not the results. Afterwards, resistance for all the electrode's embroidering configurations was assessed. The objective was to find low resistance values, however, those which benefit from those results may not be the best electrodes. Optimization of samples resistance related with its cost was the key point and the last study.

4.1. Paraffin wax study

Apply a paraffin wax to the conductive thread was needed to be able to embroider electrodes for longer times. In several occasions the thread broke due to increased temperatures as a result of constant friction and consequently, turned the process really tedious. A resistance study of the R results for paraffined and not paraffined threads was conducted. The electrodes configurations are W-3,5-0,2 (**Figure 4.1**) and W-7-0,4 (**Figure 4.2**).

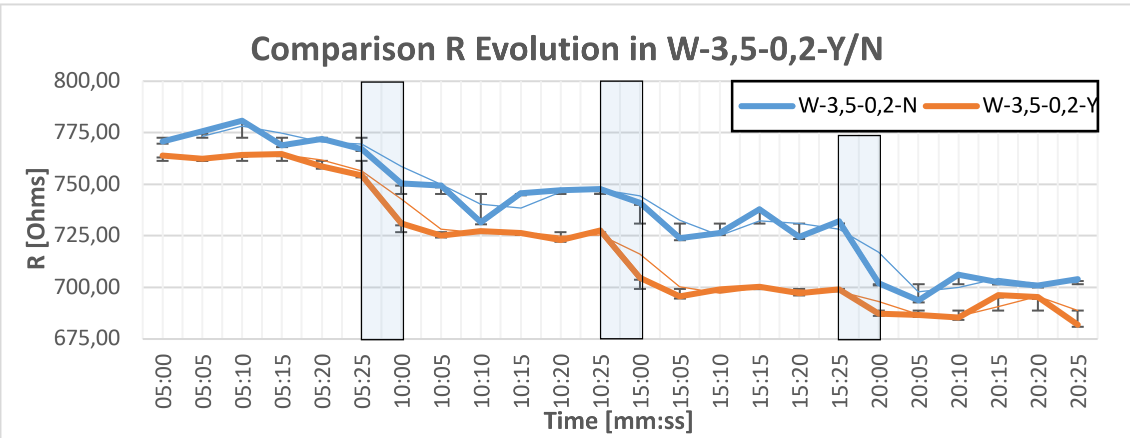


Figure 4.1. Comparison R in W-3,5-0,2-Y/N

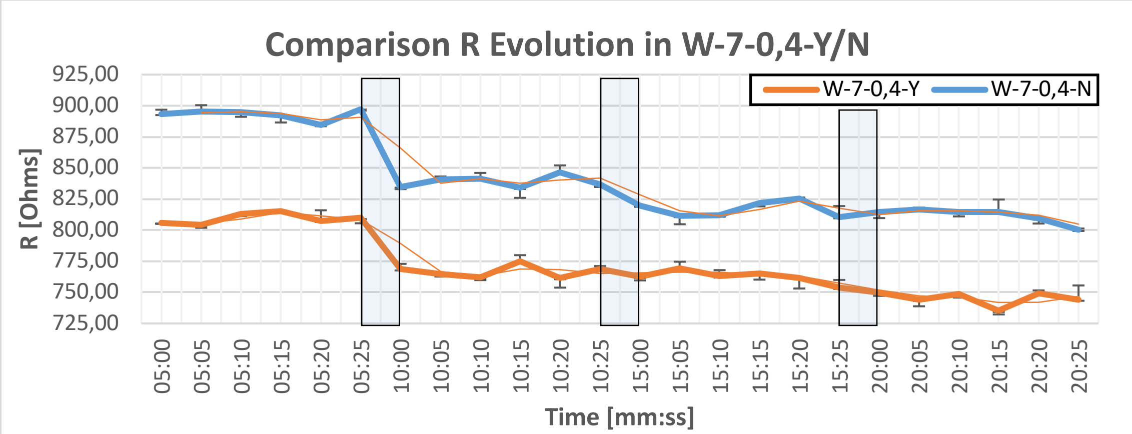


Figure 4.2. Comparison R in W-7-0,4-Y/N

In both cases the thread with an applied paraffin wax obtained lower values of resistance (**Table 4.1**).

Mean R [Ω]

	5 min	10 min	15 min	20 min
W-3,5-0,2-N	772,6	745,3	731	701,6
W-3,5-0,2-Y	761,4	726,8	699,3	688,8
Decrease [%]	-1,5	-2,5	-4,3	-1,8
W-7-0,4-N	893	839,1	816,7	811,7
W-7-0,4-Y	809,3	766,7	762,5	745,2
Decrease [%]	-9,4	-8,6	-6,6	-8,2

Table 4.1. Paraffin waxing threads results

As a result, it is achieved the possibility to embroider for longer periods non-stop, reducing breaking threads occurrence and even obtaining better resistance results. From now on, the electrodes to study will be paraffin waxed as well (some configurations were already embroidered and they are kept).

In those first two plots it can be seen that there is a considerable decline between the results obtained during the first 5 min period and the following one. This is a constant trend in all the samples and the main reason why the stabilization time was decided to be up to 20 min. In this very first two cases a table is been confectioned to reflect those changes numerically (**Table 4.2**).

<table>
<tr><th></th><th colspan="4">Mean R [Ω]</th></tr>
<tr><th></th><th>5 min</th><th>10 min</th><th>5 min</th><th>0 min</th></tr>
<tr><td>W-3,5-0,2-Y</td><td>761,4</td><td>726,8</td><td>699,3</td><td>688,8</td></tr>
<tr><td rowspan="3">Decrease [%]</td><td colspan="2">-4,5</td><td colspan="2"></td></tr>
<tr><td></td><td colspan="2">-3,8</td><td></td></tr>
<tr><td colspan="2"></td><td colspan="2">-1,5</td></tr>
<tr><td>W-7-0,4-Y</td><td>809,3</td><td>766,7</td><td>762,5</td><td>745,2</td></tr>
<tr><td rowspan="3">Decrease [%]</td><td colspan="2">-5,3</td><td colspan="2"></td></tr>
<tr><td></td><td colspan="2">-0,54</td><td></td></tr>
<tr><td colspan="2"></td><td colspan="2">-2,2</td></tr>
</table>

Table 4.2. Resistance tendency

4.2. Resistance study

4.2.1. Weave – Short Stitch – Overview

All the weave-short stitch samples were embroidered before the application of the paraffin wax coating. Actually, it was decided to do so considering that the embroidering of the sample with smallest stitch spacing (W-3,5-0,2-N) was the most tedious to craft. Despite those technical difficulties it obtained the lowest resistance results (**Figure 4.3**). A trend can be easily identified in those results. Smallest stitch spacings represents lowest resistance.

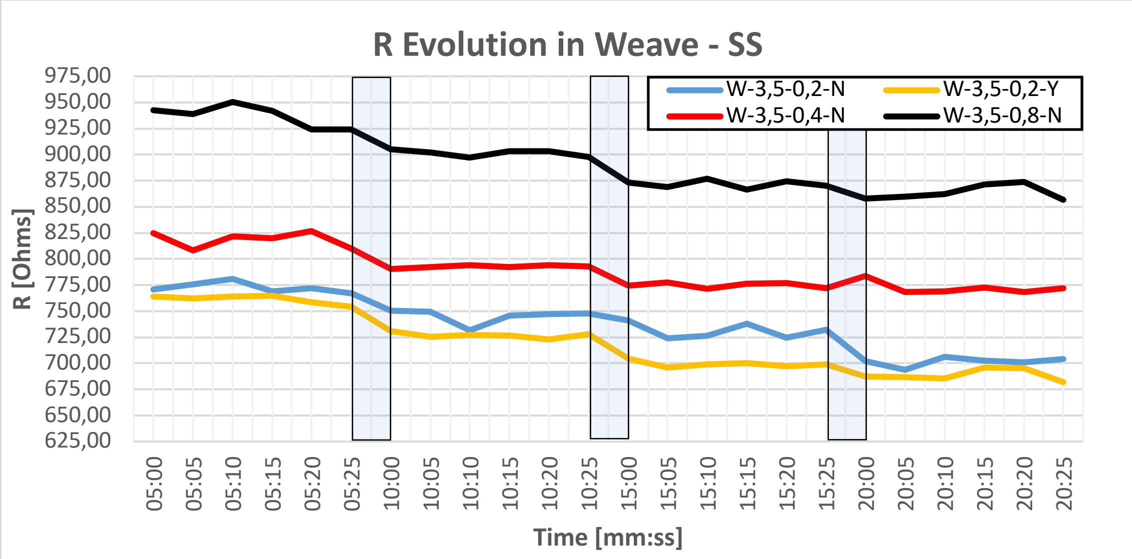


Figure 4.3. Resistance in W-ST samples

4.2.2. Weave – Long Stitch – Overview

Yet again, the trend remains the same (**Figure 4.4**). The sample with smallest stitch spacing represent the lowest resistance for weave-long stitch samples. This time, the configuration W-7-0,3-Y, is the best electrode. A sample with a 0,2 spacing (W-7-0,2-Y) was also produced but after assessing its resistance values it was taken off the study, in the following subsection there is more about it.

From the figure it can be extracted as well that, despite of the general trend, the sample with 0,6 spacing obtained better results compared with 0,4 spacing.

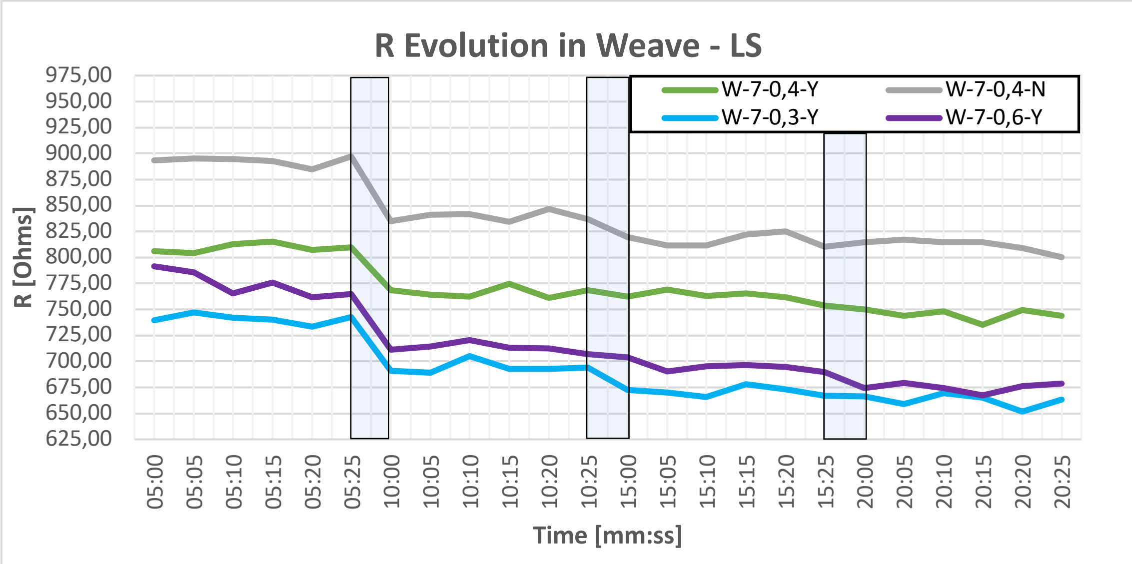


Figure 4.4. Resistance in W-LT samples

4.2.2.1. W-7-0,2-Y

The sample W-7-0-2-Y was not a special or rare electrode to craft. The procedure was as smooth as the other wax coated bioelectrodes. The conductive thread did not break at any point and the final product did not seem to be strained. However, the results were quite different (**Figure 4.5**).

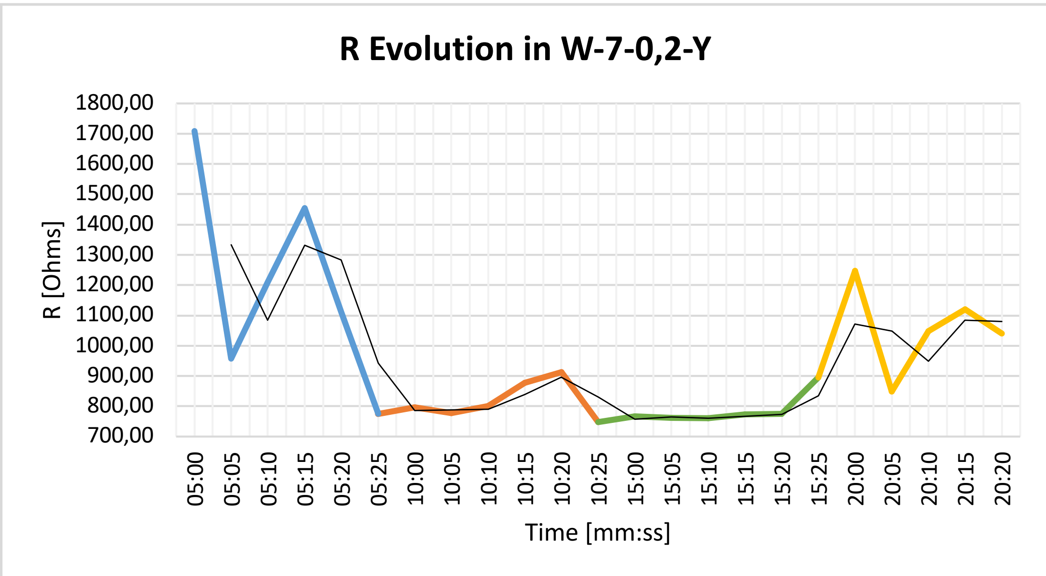


Figure 4.5. Resistance in W-7-0,2-Y

The pattern remains the same, bigger R values for the first period and then it stabilizes for the following ones. However, this rarely strong sawtooth behaviour with R changing up to 1000 Ω (>110% more than general values) and the final upturn lead to discard this study. This result might be caused by mechanical defects on the thread or on the embroidering process somehow.

4.2.3. Weave general overview

The following plot (**Figure 4.6**) represent all the resistance studies for all the weave samples embroidered. Every single figure with their error represented as well can be found on the appendix.

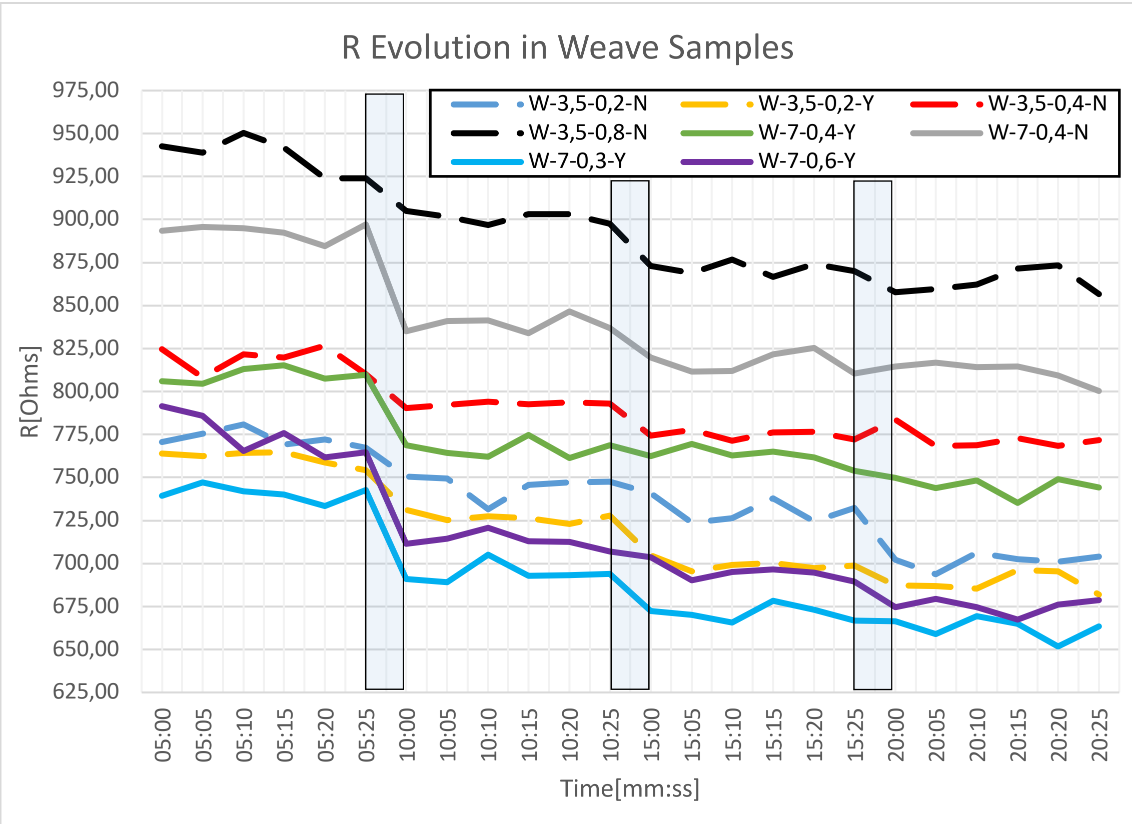


Figure 4.6. Resistance overview in weave samples

As it has been told, samples not paraffin waxed obtain worst resistance values in general. Short and long stitches can now be compared. The results obtained tell that the two out of the three best crafted electrodes are embroidered with long stitch, top one is W-7-0,3-Y followed by W-7-0,6-Y and the third one is the sample W-3,5-0,2-Y (**Table 4.1**). However, the differences between all of them are around 30 Ω which represents less than a 4,5% of change.

	Mean R [Ω]				
	5 min	10 min	15 min	20 min	15 and 20 min
W-3,5-0,2-Y	761,4	726,8	699,3	688,8	694
W-7-0,3-Y	740,8	694,2	671,1	662,5	666,8
W-7-0,6-Y	774,1	713,2	694,9	675,1	685

Table 4.1. Best samples results

4.2.4. Satin general overview

The behaviour of the satin embroidered samples is comparable with the previous ones. There are big resistance falls between the first and second periods of study. In some of the samples (S-50-Y and S-150-Y specially) the falls between the second and third periods still considerable and it is only on the last one when it seems to stabilise for all the samples.

Despite of satin embroidered electrode's behaviours are similar to the weave samples, there is no a clear trend considering their configuration. The expected results, after assessing weave samples, would be that higher densities enhance lower resistance values. However, this is not the case, nor even the opposite idea. In this case values of resistance are mixed up or at least they do not rely on density factors. Further studies should be hold to assess the samples from other points of view.

The following figure (**Figure 4.7**) represents all the results obtained. The plot for each sample can be found in the appendices.

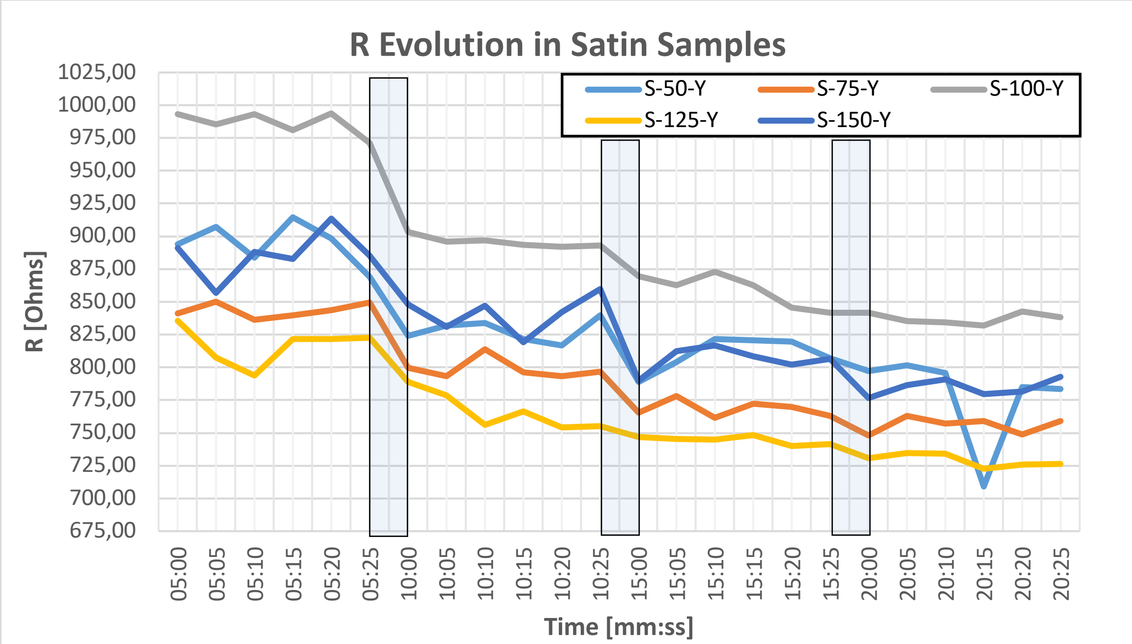


Figure 4.7. Resistance overview in satin samples

4.3. Geometry - Budget optimization

Until now resistance has been assessed but the most important point of this thesis is to find out an optimized electrode which presents good electric properties compared with its production cost. As a research study it is only quantified the materials costs.

All the electrodes have the same size and they are composed by the same elements; fabric, snap-fastener and two threads. The only difference between all of them is the quantity of both threads embroidered in, especially the silver coated silver twisted yarn conductive thread, which is really expensive.

The fabrication cost has been calculated as a relation between resistance values and grams of conductive thread. As it has been told in previous sections, the quantity of both threads is the same as they realize same patterns; conductive on the top and non-conductive at the bottom of the electrode.

The following tables (**Table 4.2, 4.3**) represents the calculations and results obtained. Only values of stabilized resistance where taken in consideration to better adjust, so R mean of period 3 and 4 (15 and 20 min).

	Mean R [Ω]			Weights [g]				R/g
	15 min	**20 min**	**15 & 20 min**	**Electrode**	**Swatch**	**Snap Fastener**	**Conductive Thread**	**-**
W-3,5-0,2-N	731	701,6	716,3	2,28	0,31	0,84	0,57	1267,7
W-3,5-0,2-Y	699,3	688,8	694	1,30	0,31	0,84	0,08	9253,8
W-3,5-0,4-N	774,8	772,3	773,6	1,74	0,31	0,84	0,30	2622,2
W-3,5-0,8-N	871,6	863,5	867,5	1,45	0,31	0,84	0,15	5688,7
W-7-0,2-Y	764,2	1033,3	898,8	2,17	0,31	0,84	0,51	1753,7
W-7-0,4-Y	762,5	745,2	753,8	1,67	0,31	0,84	0,26	2871,8
W-7-0,4-N	816,7	811,7	814,2	1,65	0,31	0,84	0,25	3224,5
W-7-0,3-Y	671,1	662,5	666,8	1,84	0,31	0,84	0,35	1932,8
W-7-0,6-Y	694,9	675,1	685	1,52	0,31	0,84	0,19	3653,3

Table 4.2.Optimization results for weave samples

	Mean R [Ω]			Weights [g]				R/g
	15 min	**20 min**	**15 & 20 min**	**Electrode**	**Swatch**	**Snap Fastener**	**Conductive Thread**	**-**
S-50-Y	810,2	778,7	794,4	1,40	0,31	0,84	0,13	6230,9
S-75-Y	768,3	755,8	762,1	1,54	0,31	0,84	0,20	3858,5
S-100-Y	859,2	837,4	848,3	1,69	0,31	0,84	0,27	3112,9
S-125-Y	744,3	729	736,6	1,80	0,31	0,84	0,33	2249,3
S-150-Y	806	784,7	795,4	1,90	0,31	0,84	0,38	2121

Table 4.3.Optimization results for satin samples

Representing on a plot the previous information it is obtained the following figure (**Figure 4.8**).

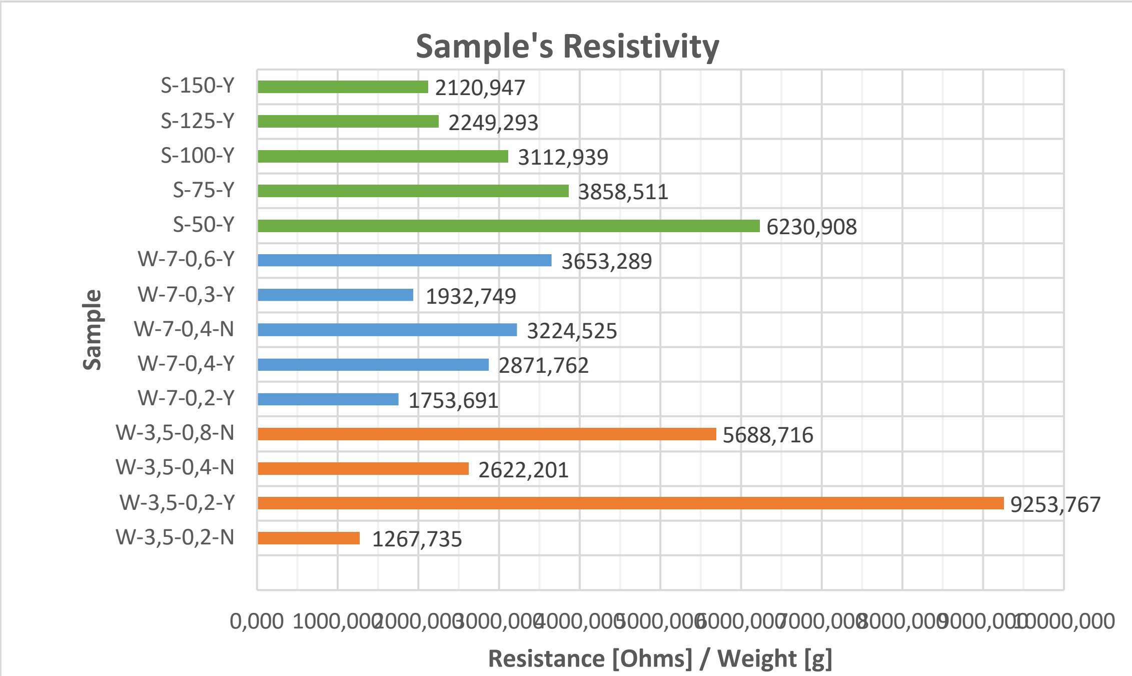


Figure 4.8. Optimization - Resistance / Cost

It is clear that the best results in this study has been obtained by W-3,5-0,2-Y. The relation between resistance and weight of conductive thread is by far the best one of all the samples. Considering that satin samples had been to be discarded due to their inconsistency, the following electrodes to take into account are W-3,5-0,8-N and W-7-0,6-Y. For the first one, a future study with the paraffin wax applied may obtain better results as well.

Considering only material costs W-3,5-0,2-Y it is the best electrode, however it took up to 90 min of embroidering process which could make tilt the balance in favour of W-3,5-0,8-N which crafting time was shorter.

4.4. Results contrasts

To quantify how this thesis has improved and evolved the methodology it is necessary to compare the results obtained with the ones achieved in the last project held on the UPC and the one which we are based on (found on the bibliography as [1]).

The following table (**Table 4.4**) represent the resistance (R) and reactance (X_c) values for both the thesis. All the R and X_c showed from this present thesis represent the mean obtained for stabilized periods (15 -20 min). Their nomenclature has been changed to be able to compare easily. Only their best samples are presented.

	Thesis	Sample	R [Ω]	Reduction [%]	$\lvert X_c\rvert$ [Ω]	Reduction [%]
Best Samples	Present	**W-3,5-0,2-Y**	694		104.075	
		W-7-0,3-Y	667		107.305	
		W-7-0,6-Y	685		112.163	
	Past	**W-3,5-0,4-N**	2750	72	261.000	57
	Present	**W-3,5-0,4-N**	774		111.260	
	Past	**W-7-0,4-N**	2750	70	244.000	52
	Present	**W-7-0,4-N**	814		116.165	
	Present	**W-7-0,4-Y**	754		111.475	
	Past	**W-3,5-0,8-N**	2750	68	284.000	58
	Present	**W-3,5-0,8-N**	868		119.778	
	Past	**S-50-N**	1280	38	296.000	60
	Present	**S-50-Y**	794		117.638	
	Past	**S-150-N**	2610	70	240.000	56
	Present	**S-150-Y**	795		106.578	

Table 4.4. Present thesis results v last thesis

In general terms, the present study presents, for the comparable samples, a reduction between 68 to 72% of the resistance values. And, on the other hand, reactance values are between 52 to 60% lower as well. However, those are not the best samples obtained in this current thesis. That means that through the detailed methodology and know how presented in this thesis the electrodes values are far better and following studies may consider to make theirs our results.

Those big differences on the obtained results for the same configurations may be from two basic points. First of all, the application of the paraffin wax which enhance not only higher productions but better results as well. And on the other hand, the measurement protocol. Stabilization time is more adequate to its final application and the set up permits more reliability and human free errors.

5. Conclusion

After realizing this thesis one more step for the development of textile embroidered electrodes has been done. Swap from conventional old-fashioned technology to this cutting-edge know how is everyday closer.

First of all, it has been demonstrated that applying a paraffin wax coating to the conductive thread allow a much consistent manufacture process of electrodes. Threads breaking are not a problem anymore rather than the starting point where it was common to be forced to thread and re-start the process several times to craft one single sample.

Regarding other projects and papers, a more trustworthy measurement procedure has been defined. On one hand due to electrodes evaluation set-up, which enhances free human interference. Decreasing the probability of user's measurement error was a secondary goal but considerably influential for the quality and reliability of the results. On the other hand, stabilization times has been assessed and must be at least for 15 minutes. The longer the stabilization time the most credible will the results be as this is a technology thought to be used constantly for long periods of time.

Considering this thesis results, weave embroidered samples not only obtained better resistance results but also a trend can be read. Actually, this is the most important point. Follow and describe a certain behaviour enhance us to create mathematical models to run simulations and obtain ideal electrodes much faster than a trial and error methodology. In this thesis 7 mm stitches achieved better resultant rather than 3,5 mm. Moreover, as for stitch spacings, in both cases smallest ones lead to lower resistance values. Consequently, for future projects long stitches but with less spacings should be taken as a starting point. On the other hand, satin patterns displayed non-sense performances. Even working with high densities as it has been done with weave samples did not seem to be profitable. Other different perspectives may obtain understandable results.

Considering now the impedance components values, R and X_c, of the last project [1] from where this thesis is based on, a quality leap has been achieved. Around 70% in resistances values and 55% for reactance values reduction has been achieved on the same embroidered textile electrodes configurations. However, this last one are not the best ones in this thesis as other different configuration turned out to obtain lower resistance values and so enhancing lower Z_p and at the end enabling an easiest current flow.

6. Planification

The following table (**Table 6.1**) represents roughly the planification followed to realise the thesis.

TASK NAME	START DATE	DUE DATE	DURATION [Days]
Bibliography Research and State of The Art	1/8/19	16/9/19	**46**
Human potential measurements - theory, applications -	1/8/19	19/8/19	18
Noise sources - electronic correction -	19/8/19	28/8/19	9
Wearable textile embroidered sensors	28/8/19	16/9/19	19
Objectives Set Up	16/9/19	23/9/19	**7**
Laboratory Training	23/9/19	7/10/19	**14**
Software training	23/9/19	25/9/19	2
Firsts trial samples crafting	25/9/19	2/10/19	7
Firsts trial samples measurements	2/10/19	7/10/19	5
Paraffin wax study for 2 samples	7/10/19	28/10/19	**21**
Design and Embroidering	28/10/19	25/11/19	**28**
Final samples embroidering	28/10/19	24/11/19	27
Samples preparations - Cutting and fast-fasteners attachment -	24/11/19	25/11/19	1
Measurement testing	25/11/19	18/12/19	**23**
PET plastic, wood holders' systems	25/11/19	2/12/19	7
Design and building of the 3D holders	2/12/19	4/12/19	2
Final resistance measurements - 3D holders -	4/12/19	16/12/19	12
Weight measurements	16/12/19	18/12/19	2

Documentation Generation	18/12/19	14/1/20	**27**
Data handling and post-processing	18/12/19	3/1/20	16
Report	18/12/19	10/1/20	16
Review and final version	10/1/20	14/1/20	4
Delivery	14/1/20	15/1/20	**1**

Table 6.1. Tasks planification

If we plot the previous information, the following Gantt is obtained (**Figure 6.1**).

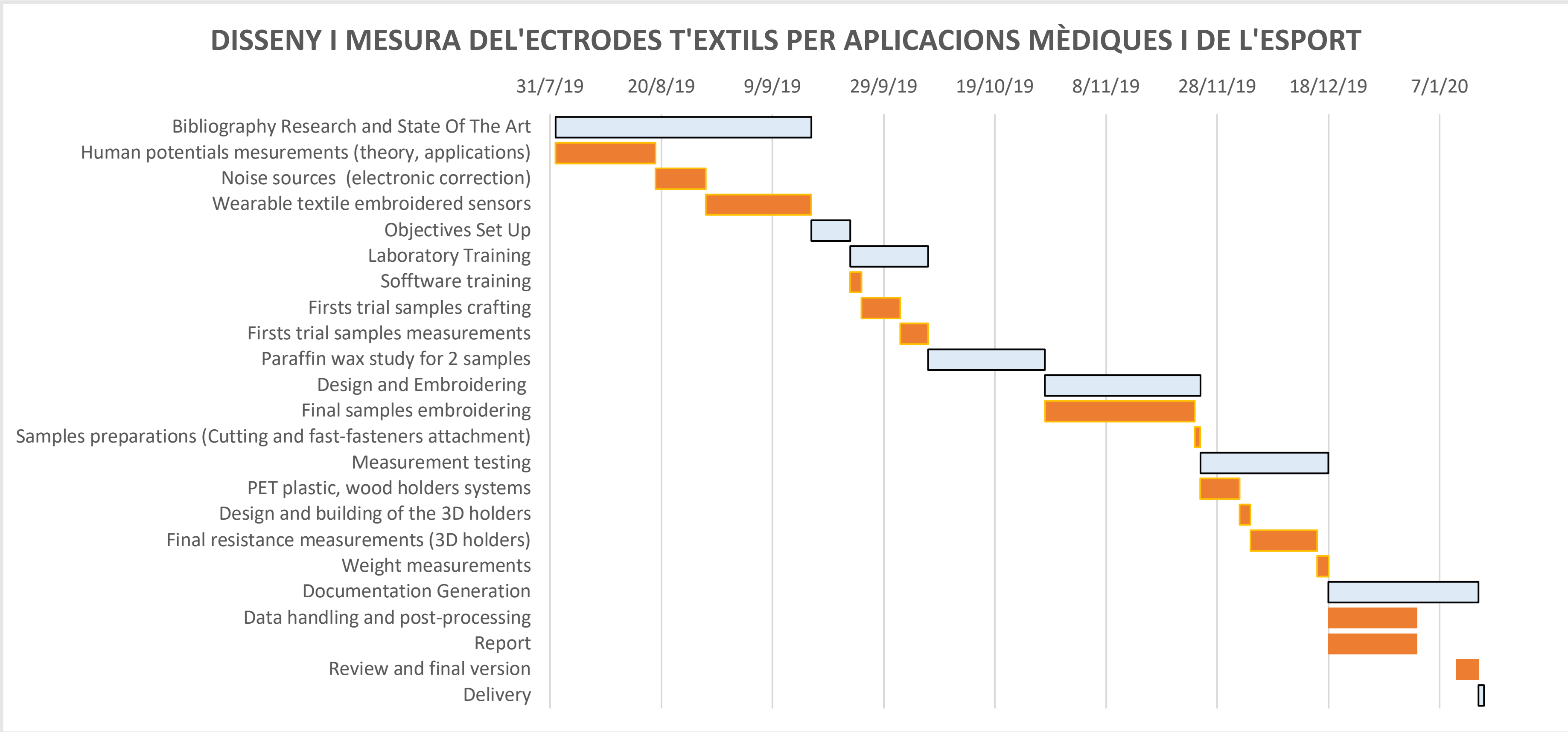


Figure 6.1. Gantt of the thesis

7. Bibliography

[1] I.Logothetis, R. Fernandez-Garcia, O. Troynikov, P. Dabnichki, E. Pirogova, and I. Gil, "Embroidered electrodes for bioelectrical impedance analysis: impact of surface area and stitch parameters", in *Meas. Sci. Technol.*, 30, Sep 2019, pp. 12.

[2] Scilingo EP, Gemignani A, Paradiso R, et al., "Performance evaluation of sensing fabrics for monitoring physiological and biomedical variable", *IEE Trans. Inf. Technol. Biomed.* 2005

[3] B. Michael and M. Howard, "Learning predictive movement model from fabric-mounted wearable sensors", *IEEE Trans. Neural Syst. Rehabil. Eng*., to be published.

[4] Y. Ouyang and W.J. Chappell, "High frequency properties of electro-textiles for wearable antennae applications," *IEEE Trans. Antennas Propag.,* vol. 56, no. 2, pp. 381-389, Feb 2008.

[5] C. Zysset, T. W. Kinkeldei, N. Munzenriede, K. Cherenack, and G. Troster, "Integration method for electronics in woven textiles," *IEEE Trans. Compon, Packag. Manuf. Technol.,* vol. 2, no. 7, pp. 1107-1117, Jul. 2012.

[6] A. Shafti, R. B. R. Manero, A. M. Borg, K. Althoefer, and M. J. Howard, "Embroidered Electromyography: A Systematic Design Guide", in *IEEE Trans. Neural Syst. Rehabil. Eng.,* vol. 25, no. 9, 2016.

[7] O.Tikkanen, M. Hu, T. Vilavuo, P. Tolvanen, S. Cheng, and T. Finni, "Ventilatory Threshold during incremental running can be estimated using EMG shorts," *Physiol. Meas.,* vol. 33, no. 4, pp. 604-614, 2012.

[8] L. Peppoloni, A. Filippeschi, and E. Ruffaldi, "Assessment of task ergonomics with an upper limb wearable device," in *Proc. MED,* Palermo, Italy, Jun. 2014, pp. 340-345.

[9] A. Shafti *et al.*, "Comfort and learnability assessment of a new soft robotic manipulator for minimally invasive surgery," in *Proc. MED,* Palermo, Italy, Jun. 2014, pp. 340-345.

[10] Merletti r, Parker PA, "Electromyography, Physiology, Engineering and Noninvasive Applications", Wiley Interscience, 2014, ISBN 0471-67580-6

[11] Mcadams E, "Biomedical electrodes for biopotential monitoring and electrostimulation", *Bio-Medical CMOS ICs* ed H J Yoo and C van Hoof (Berlin: Springer), 2011, pp 31-124.

[12] Castizo-Olier J, Irurtia A, Jemni M, Carrasco-Marginet M, Fernandez-Garcia R and Rodriguez F, "A biolectrical impedance vector analysis (BIVA) in sport and exercise: systematic review and future perspectives", *PLoS One* 13 e0197957, 2018.

[13] T Kannaian, R Neelaveni and G. Thilagavathi, "Design and development of embroidered textile electrodes for continuous measurement of electrocardiogram signals", *SJO*, 42(3) 303-318.

[14] Nescolarde L, Yanguas J, Terricabras J, Lukaski H, Alomar X, Rosell-Ferrer J and Rodas G, "Detection of muscle gap by L-BIA in muscle injuries: clinical prognosis", *Physiol. Meas.*, 2017.

[15] Conchell J C, "Bio-impedance circuit design for body worn systems" *Analog Devices*, 2014.

[16] Noveletto F, Bertemes-Filho P, and Dutra D, "Analog front-end for the integrated circuit AD5933 used in electrical bioimpedance measurements", *II Latin American Conf. on Bioimpedance IFMBE,* Proc. ed F Simini and P Bertemes-Filho, 2016, pp 48–51.

[17] Nescolarde L, Yanguas J, Lukaski H, Alomar X, Rosell-Ferrer J and Rodas G, "Localized bioimpedance to assess muscle injury" *Physiol. Meas.,* 2013.

[18] Nescolarde L, Yanguas J, Lukaski H, Alomar X, Rosell-Ferrer J and Rodas G, "Effects of muscle injury severity on localized bioimpedance measurements", *Physiol. Meas*. 2015.

[19] Harrison A P, Elbrønd V S, Riis-Olesen K and Bartels E M, "Multi-frequency bioimpedance in equine muscle assessment", *Physiol. Meas*., 2015.

[20] Cumming K, Hoyle G E, Hutchison J D and Soiza R L, "Bioelectrical impedance analysis is more accurate than clinical examination in determining the volaemic status of elderly patients with fragility fracture and hyponatraemia", *J. Nutr. Heal. Aging*., 2014.

[21] Dean D A, Ramanathan T, Machado D and Sundarajan R, "Electrical impedance spectroscopy stydy of biological tissues", *J. Electrostat.* 2008.

[22] Kyle U G et al, "Bioelectrical impedance analysis—part I: review of principles and methods", *Clin. Nutr.,* 2004.

[23] Kyle U G et al, "Bioelectrical impedance analysis—part II: utilization in clinical practice", *Clin. Nutr.* 2004.

[24] Baghbani R, Moradi M H and Shadmehr M B, "The development of a four-electrode bio-impedance sensor for identification and localization of deep pulmonary nodules", *Ann. Biomed. Eng.,* 2018.

[25] Khalil S F, Mohktar M S and Ibrahim F, "The theory and fundamentals of bioimpedance analysis in clinical status monitoring and diagnosis of diseases", *Sensors, 2014.*

[26] King R J, Clamp J A, Hutchinson J W and Moran C G, "Bioelectrical impedance: a new method for measuring posttraumatic swelling", *J. Orthop. Trauma,* 2007.

[27] Lukaski H C and Moore M, "Bioelectrical impedance assessment of wound healing", *J. Diabetes Sci. Technol.*, 2012.

[28] Swisher S L et al, "Impedance sensing device enables early detection of pressure ulcers in vivo", *Nat. Commun.,* 2015.

[29] McAdams E, "Bioelectrodes Encyclopedia of Medical Devices and Instrumentation", *2nd edn vol 1, ed J G Webster (New York: Wiley)*, 2006, pp 120–66.

[30] Nescolarde L, Lukaski H, De Lorenzo A, De-Mateo-Silleras B, Redondo-Del-Río M P and Camina-Martín M A, "Different displacement of bioimpedance vector due to Ag/AgCl electrode effect", *Eur. J. Clin. Nutr.*, 2016.

[31] Karilainen A, Hansen S and Muller J, "Dry and capacitive electrodes for long-term ECG.monitoring", In: *8th Annual Workshop on Semiconductor Advances,* 2005, p. 156.

[32] Kaappa E S, Joutsen A, Cömert A and Vanhala J, "The electrical impedance measurements of dry electrode materials for the ECG measure", 2017.

[33] Li G, Lu X, Wang Z, Rong Y, Hu R, Luo Z and Wang Y. "All-solid-state carbonate-selective electrode based on screen-printed carbon paste electrode", *Meas. Sci. Technol*., 2017.

[34] Posada-Quintero H, Noh Y, Eaton-Robb C, Florian J P and Chon K H, "Feasibility testing of hydrophobic carbon electrodes for acquisition of underwater surface electromyography data", *Ann. Biomed. Eng.,* 2018.

[35] Jung H, Moon J, Baek D, Lee J, Choi Y and Hong J, "CNT/PDMS Composite flexible dry electrodes for longterm ECG monitoring", *IEEE Trans. Biomed. Eng*., 2012.

[36] Kim T, Park J, Sohn J, Cho D and Jeon S, "Bioinspired, highly stretchable, and conductive dry adhesives based on 1D–2D hybrid carbon nanocomposites for all-in-one ECG electrodes" *ACS Nano*, 2016.

[37] Lee S M, Byeon H J, Lee J H, Baek D H, Lee K H, Hong J S and Lee S H, "Self-adhesive epidermal carbon nanotube electronics for tether-free long-term continuous recording of biosignals" *Sci. Rep*., 2014.

[38] Liu B, Luo Z, Zhang W, Tu Q and Jin X, "Carbon nanotube-based self-adhesive polymer electrodes for wireless long-term recording of electrocardiogram signals", *J. Biomater. Sci. Polym. Ed.*, 2016.

[39] Liu B, Luo Z, Zhang W, Tu Q and Jin X, "Silver nanowirecomposite electrodes for long-term electrocardiogram measurements", *Sens. Actuators,* 2016.

[40] Zhao Y, Cao Y, Liu J, Zhan Z, Li X and Li W J, "Single-wall carbon nanotube-coated cotton yarn for electrocardiography transmission", *Micromachines,* 2018.

[41] Imani S, Bandodkar A J, Mohan A M V, Kumar R, Yu S, Wang J and Mercier P P, "A wearable chemicalelectrophysiological hybrid biosensing system for real-time health and fitness monitoring", *Nat. Commun.,* 2016.

[42] Peng H L, Liu J Q, Dong Y Z, Yang B, Chen X and Yang C S, "Parylene-based flexible dry electrode for bioptential recording", *Sensor. Actuators,* 2016.

[43] Khan Y, Pavinatto F J, Lin M C, Liao A, Swisher S L, Mann K, Subramanian V, Maharbiz M M and Arias A C, "Inkjet-printed flexible gold electrode arrays for bioelectronic interfaces", *Adv. Funct. Mater.,* 2016.

[44] Schnitker J, Adly N, Seyock S, Bachmann B, Yakushenko A, Wolfrum B and Offenhäusser A, "Rapid prototyping of ultralow-cost, inkjet-printed carbon microelectrodes for flexible bioelectronic devices" *Adv. Biosyst.,* 2018.

[45] Lee J and Yun K, "ECG Monitoring garment using conductive carbon paste for reduced motion artifacts", *Polymers*, 2017.

[46] Ameri S K, Ho R, Jang H, Tao L, Wang Y, Wang L, Schnyer D M, Akinwande D and Lu N, "Graphene electronic tattoo sensors", *ACS Nano*, 2017 .

[47] Bareket L, Inzelberg L, Rand D, David-Pur M, Rabinovich D, Brandes B and Hanein Y, "Temporary-tattoo for longterm high fidelity biopotential recordings" *Sci. Rep.*, 2016.

[48] EMG Block Diagram. Available at: http://10.bargain.danis-schreibwelt.de/emg-block-diagram.html. Last Access: 01/01/2020.

[49] R. Merletti, A. Botter, A. Troiano, E. Merlo, and M. A. Minetto, "Technology and instrumentation for detection and conditioning of the surface electromyographic signal; State of the art", *Clin. Biomech.,* vol. 24, no. 2, pp. 122-134, Feb. 2008.

[50] Conductive thread caracteristics. Available at: https://www.shieldextrading.net/products/yarns-threads/ Last Acces: 02/01/2020.

[51] Gil I, Fernández-García R and Tornero J A, "Embroidery manufacturing techniques for textile dipole antenna applied to wireless body area network", *Text. Res. J.,* 2018.

8. Appendices

8.1. Appendix A

In this first appendix all the results and calculations related with the resistance are presented in a table.

Stitch Type	Stitch Length	Stitch Spacing [mm]	Number Stitches	Paraffin Wax (Y/N)	Code	R [Ohms]							
						01:00	05:00	05:05	05:10	05:15	05:20	05:25	AVG 5 min
W	3,5	0,2	4670	N	W-3,5-0,2-N	876,08	770,71	775,60	780,85	769,05	772,16	767,19	772,59
					Error		1,88	-3,01	-8,26	3,54	0,43	5,40	
W	3,5	0,2	4673	Y	W-3,5-0,2-Y	889,26	764,05	762,36	764,22	764,69	758,57	754,38	761,38
					Error		-2,67	-0,98	-2,84	-3,31	2,81	7,00	
W	3,5	0,4		N	W-3,5-0,4-N	843,18	824,44	808,30	821,69	819,69	826,65	810,25	818,50
					Error		-5,94	10,20	-3,19	-1,19	-8,15	8,25	
W	3,5	0,8		N	W-3,5-0,8-N	1185,4	942,64	939,04	950,37	942,02	924,13	923,92	937,02
					Error		-5,62	-2,02	-13,35	-5,00	12,89	13,10	
W	7	0,2		Y	W-7-0,2-Y	1219,3	1708,80	957,81	1209,80	1453,70	1112,30	6022,30	2077,45
					Error		368,65	1119,64	867,65	623,75	965,15	-3944,85	
W	7	0,4	1575	Y	W-7-0,4-Y	962,05	806,01	804,38	813,07	815,25	807,49	809,66	809,31

					Error		3,30	4,93	-3,76	-5,94	1,82	-0,35	
W	**7**	**0,4**	**1575**	**N**	**W-7-0,4-N**	1086,7	893,49	895,52	894,86	892,47	884,54	897,17	893,01
					Error		-0,48	-2,51	-1,85	0,54	8,47	-4,16	
W	**7**	**0,3**	**1990**	**Y**	**W-7-0,3-Y**	876,89	739,33	747,13	742,10	740,20	733,52	742,72	740,83
					Error		1,50	-6,30	-1,27	0,63	7,31	-1,89	
W	**7**	**0,6**	**1190**	**Y**	**W-7-0,6-Y**	964,8	791,47	785,92	765,32	775,77	761,57	764,72	774,13
					Error		-17,34	-11,79	8,81	-1,64	12,56	9,41	

R [Ohms]												
10:05	**10:10**	**10:15**	**10:20**	**10:25**	**AVG 10 min**	**15:00**	**15:05**	**15:10**	**15:15**	**15:20**	**15:25**	**AVG 15 min**
749,40	731,61	745,67	747,14	747,72	745,33	741,01	723,90	726,39	737,90	724,50	732,10	730,97
-4,07	13,72	-0,34	-1,81	-2,39		-10,04	7,07	4,58	-6,93	6,47	-1,13	
725,20	727,32	726,45	723,12	727,70	726,81	704,74	695,61	699,08	700,17	697,12	698,95	699,28
1,61	-0,51	0,36	3,69	-0,89		-5,46	3,67	0,20	-0,89	2,16	0,33	
792,05	793,92	792,43	793,88	792,98	792,62	774,49	777,62	771,42	776,33	776,59	772,25	774,78
0,57	-1,30	0,19	-1,26	-0,36		0,29	-2,84	3,36	-1,55	-1,81	2,53	
901,81	896,85	903,21	903,21	897,44	901,25	872,99	868,74	876,88	866,60	874,23	870,11	871,59
-0,56	4,40	-1,96	-1,96	3,81		-1,40	2,85	-5,29	4,99	-2,64	1,48	
796,61	777,55	800,82	877,52	912,81	823,32	747,84	766,85	761,77	760,73	773,24	775,02	764,24
26,70	45,77	22,49	-54,21	-89,50		16,40	-2,61	2,47	3,51	-9,00	-10,78	
764,37	762,22	774,80	761,31	768,69	766,66	762,57	769,35	762,87	765,14	761,51	753,70	762,52

2,29	4,44	-8,14	5,35	-2,03		-0,05	-6,83	-0,35	-2,62	1,01	8,82	
840,81	841,53	834,06	846,68	836,73	839,11	819,72	811,53	811,78	821,70	825,20	810,51	816,74
-1,70	-2,42	5,05	-7,57	2,38		-2,98	5,21	4,96	-4,96	-8,46	6,23	
689,28	704,93	692,88	693,01	693,78	694,15	672,36	670,05	665,80	678,17	673,25	666,78	671,07
4,87	-10,78	1,27	1,14	0,37		-1,29	1,02	5,27	-7,10	-2,18	4,29	
714,43	720,79	712,98	712,72	707,07	713,22	703,64	690,13	694,96	696,40	694,72	689,51	694,89
-1,21	-7,57	0,24	0,50	6,15		-8,75	4,76	-0,07	-1,51	0,17	5,38	

R [Ohms]						
20:00	**20:05**	**20:10**	**20:15**	**20:20**	**20:25**	**AVG 20 min**
702,01	693,74	706,18	702,54	700,94	704,03	701,57
-0,44	7,83	-4,61	-0,97	0,63	-2,46	
687,21	686,68	685,28	696,14	695,49	681,92	688,79
1,58	2,11	3,51	-7,35	-6,70	6,87	
783,73	768,32	768,77	772,86	768,35	771,86	772,32
-11,42	4,00	3,55	-0,54	3,97	0,46	
857,61	859,41	862,26	871,34	873,52	856,66	863,47
5,86	4,06	1,21	-7,87	-10,05	6,81	

895,25	1247,20	848,80	1048,10	1120,10	1040,30	1033,29
138,04	-213,91	184,49	-14,81	-86,81	-7,01	
749,93	743,96	748,45	735,22	749,18	744,17	745,15
-4,78	1,19	-3,30	9,93	-4,03	0,98	
814,44	816,85	814,32	814,65	809,31	800,30	811,65
-2,80	-5,21	-2,68	-3,01	2,34	11,35	
666,41	658,96	669,46	665,07	651,73	663,54	662,53
-3,88	3,57	-6,93	-2,54	10,80	-1,01	
674,64	679,41	674,54	667,36	675,96	678,63	675,09
0,45	-4,32	0,55	7,73	-0,87	-3,54	

					R [Ohms]							
Stitch Type	**%**	**Number Stitches**	**Paraffin Wax (Y/N)**	**Code**	**01:00**	**5:00**	**05:05**	**05:10**	**05:15**	**05:20**	**05:25**	**AVG 5 min**
S	**50**	**960**	**Y**	**S-50-Y**	1070,8	894,05	907,00	883,86	914,48	898,42	869,17	894,50
				Error		0,45	-12,50	10,64	-19,98	-3,92	25,33	
S	**75**	**1300**	**Y**	**S-75-Y**	933,24	841,35	850,09	836,12	839,83	843,84	849,27	843,42
				Error		2,07	-6,67	7,30	3,59	-0,42	-5,85	
S	**100**	**1750**	**Y**	**S-100-Y**	1254,1	993,03	985,28	993,36	980,96	993,77	971,23	986,27
				Error		-6,76	0,99	-7,09	5,31	-7,50	15,04	
S	**125**	**1970**	**Y**	**S-125-Y**	865,16	835,53	807,53	793,81	821,73	821,50	822,68	817,13
				Error		-18,40	9,60	23,32	-4,60	-4,37	-5,55	

S	**150**	**2270**	**Y**	**S-150-Y**	994,59	891,19	856,59	887,95	882,83	913,49	885,31	886,23
				Error		-4,96	29,64	-1,72	3,40	-27,26	0,92	

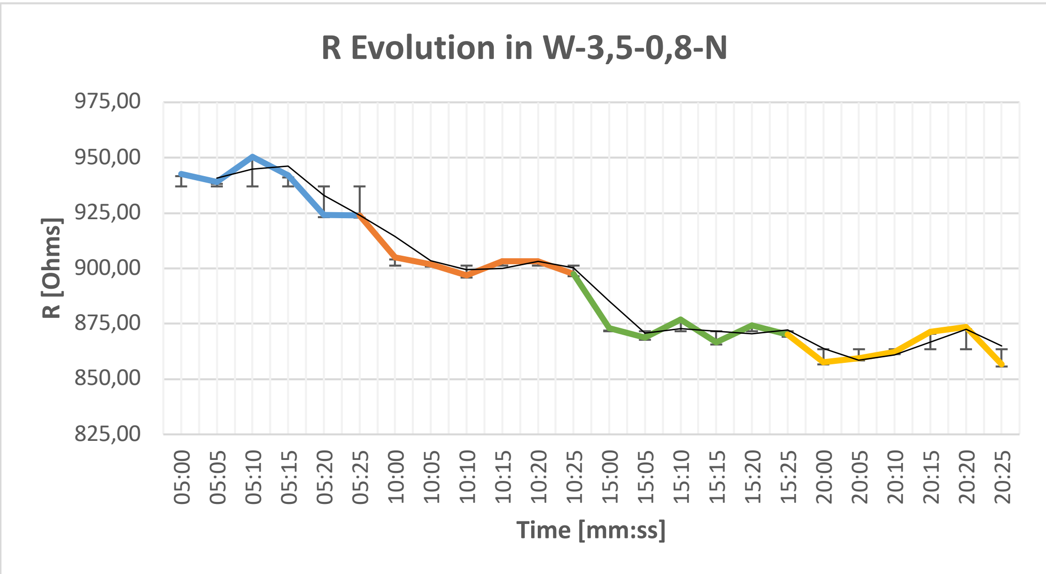
R [Ohms]													
10:00	**10:05**	**10:10**	**10:15**	**10:20**	**10:25**	**AVG 10 min**	**15:00**	**15:05**	**15:10**	**15:15**	**15:20**	**15:25**	**AVG 15 min**
824,29	831,88	833,81	821,57	816,96	839,75	828,04	788,77	803,86	821,43	820,47	819,68	807,02	810,21
3,75	-3,84	-5,77	6,47	11,08	-11,71		21,43	6,34	-11,23	-10,27	-9,48	3,18	
799,67	793,34	813,63	796,42	793,12	796,73	798,82	765,50	777,97	761,30	772,18	770,04	763,00	768,33
-0,85	5,48	-14,81	2,40	5,70	2,09		2,83	-9,64	7,03	-3,85	-1,71	5,33	
903,23	896,07	897,05	893,37	892,04	892,75	895,75	869,56	862,81	872,96	862,80	845,38	841,60	859,19
-7,48	-0,32	-1,30	2,38	3,71	3,00		-10,37	-3,62	-13,78	-3,61	13,81	17,59	
788,82	778,77	756,29	766,27	754,23	755,36	766,62	746,68	745,15	744,67	748,14	740,07	741,26	744,33
-22,20	-12,15	10,33	0,35	12,39	11,26		-2,35	-0,82	-0,34	-3,81	4,26	3,07	
848,21	830,67	846,96	819,32	842,35	859,72	841,21	789,90	812,30	816,67	808,34	802,18	806,62	806,00
-7,01	10,54	-5,76	21,89	-1,14	-18,52		16,10	-6,30	-10,67	-2,34	3,82	-0,62	

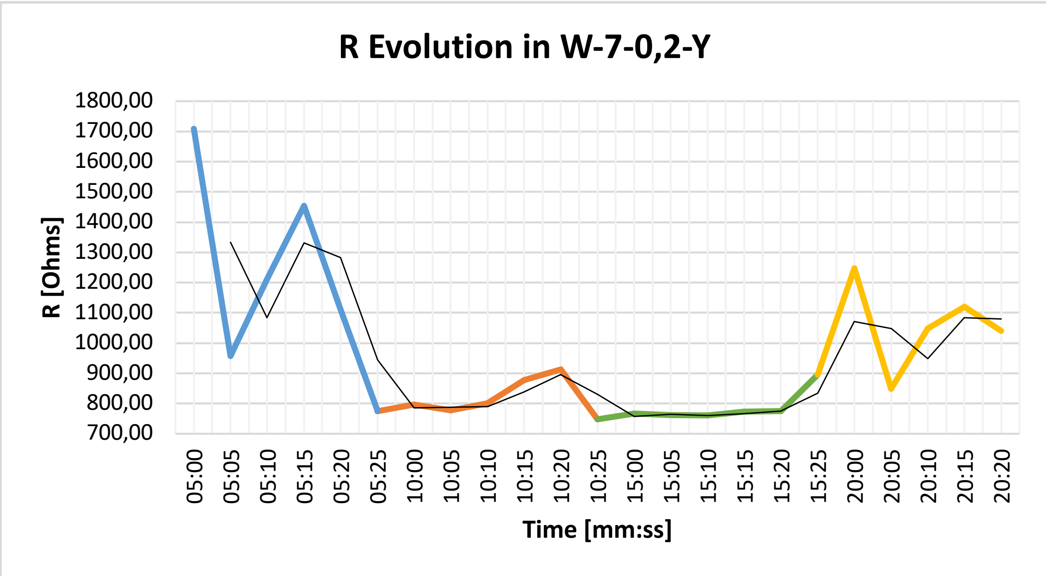
R [Ohms]						
20:00	**20:05**	**20:10**	**20:15**	**20:20**	**20:25**	**AVG 20 min**
797,10	801,69	795,75	709,07	785,20	783,25	778,68
-18,42	-23,01	-17,07	69,61	-6,52	-4,57	
748,04	762,86	757,01	759,12	748,75	758,90	755,78
7,74	-7,08	-1,23	-3,34	7,03	-3,12	
841,60	835,40	834,55	831,88	842,41	838,36	837,37
-4,23	1,97	2,82	5,49	-5,04	-0,99	
730,50	734,52	733,99	722,63	725,86	726,25	728,96
-1,54	-5,56	-5,03	6,33	3,10	2,71	
776,60	786,63	790,66	779,80	781,69	792,87	784,71
8,11	-1,92	-5,95	4,91	3,02	-8,16	

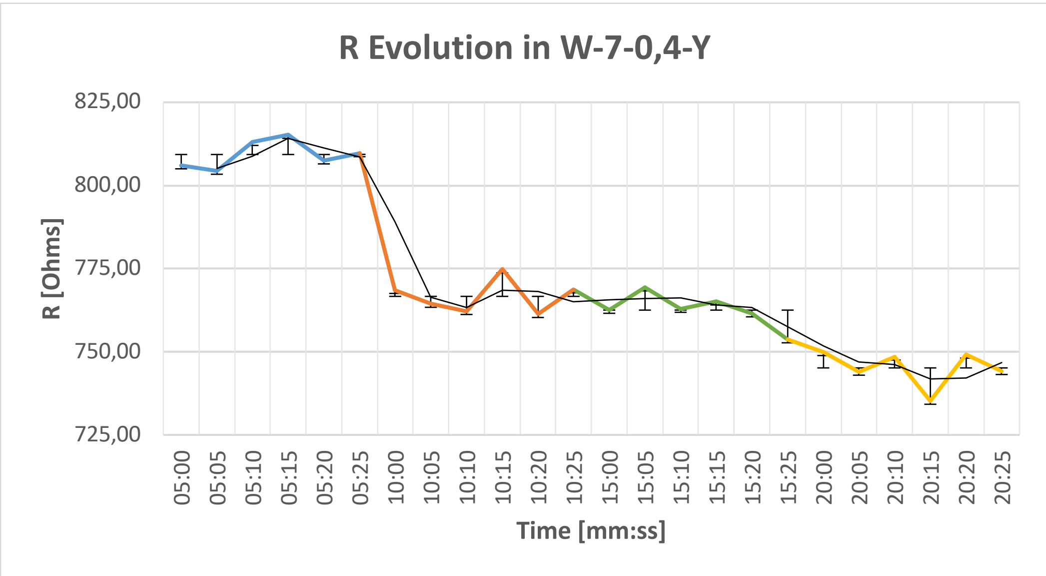
8.2. Appendix B

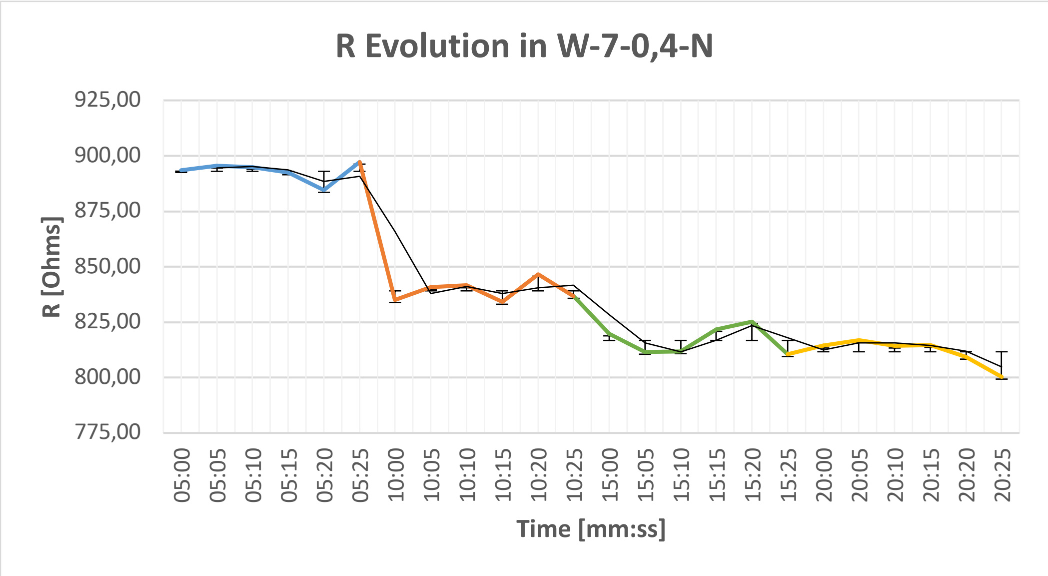
In this second appendix all the plots related with the resistance results and their related errors are presented. Weave samples to begin and satin following.

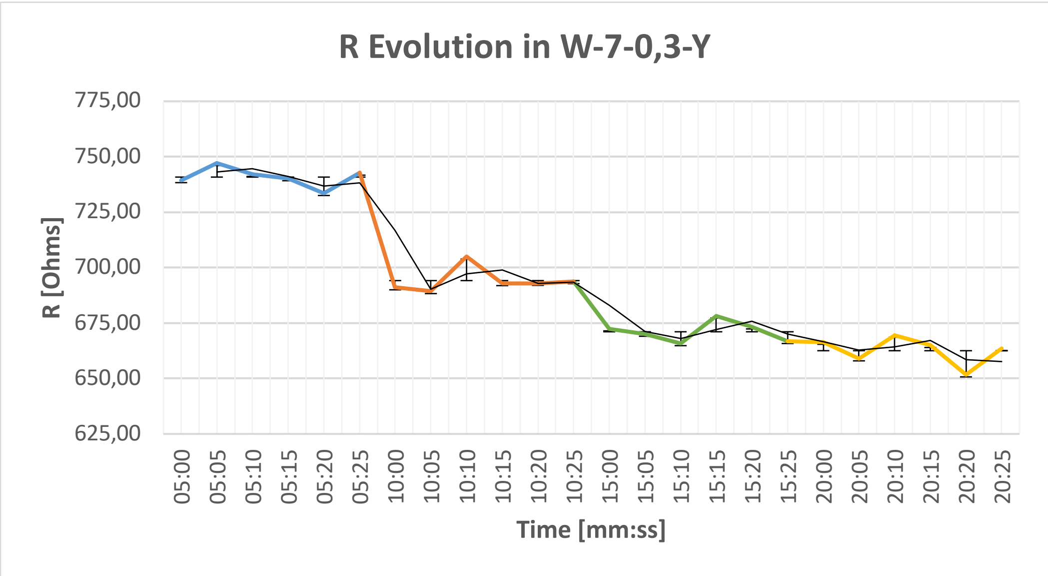

R Evolution in W-3,5-0,2-Y
800,00
775,00
750,00
725,00
700,00
675,00
R [Ohms]
05:00
05:05
05:10
05:15
05:20
05:25
10:00
10:05
10:10
10:15
10:20
10:25
15:00
15:05
15:10
15:15
15:20
15:25
20:00
20:05
20:10
20:15
20:20
Time [mm:ss]

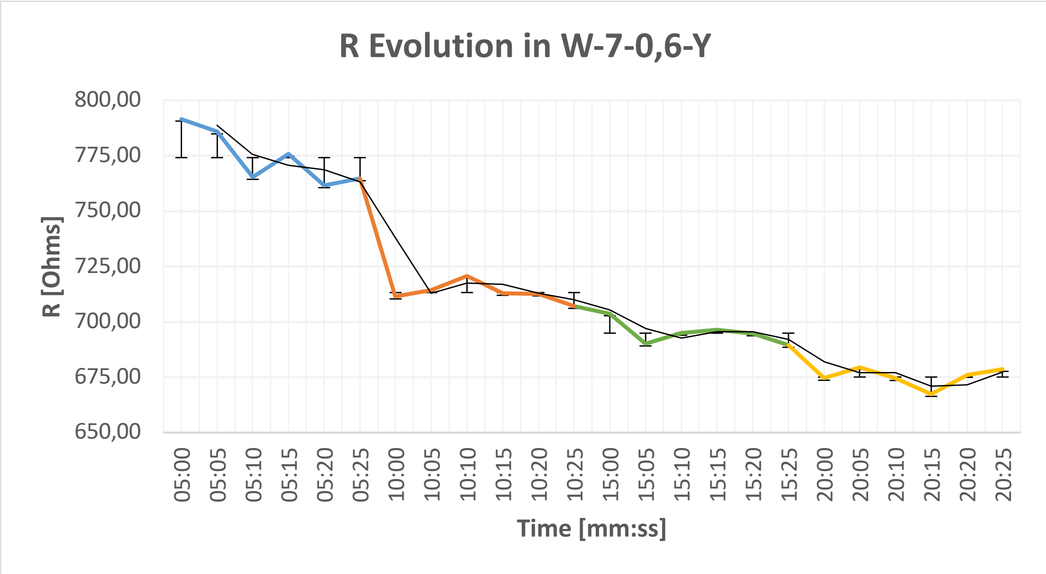

R Evolution in W-3,5-0,8-N
975,00
950,00
925,00
900,00
875,00
850,00
825,00
R [Ohms]
05:00
05:05
05:10
05:15
05:20
05:25
10:00
10:05
10:10
10:15
10:20
10:25
15:00
15:05
15:10
15:15
15:20
15:25
20:00
20:05
20:10
20:15
20:20
20:25
Time [mm:ss]

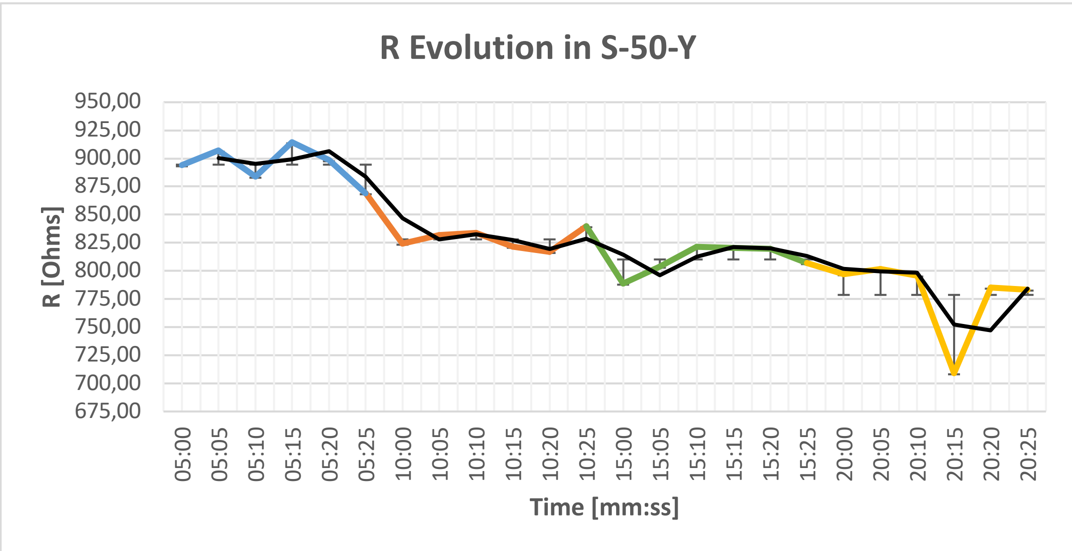

R Evolution in W-7-0,2-Y
R [Ohms]
1800,00
1700,00
1600,00
1500,00
1400,00
1300,00
1200,00
1100,00
1000,00
900,00
800,00
700,00
05:00
05:05
05:10
05:15
05:20
05:25
10:00
10:05
10:10
10:15
10:20
10:25
15:00
15:05
15:10
15:15
15:20
15:25
20:00
20:05
20:10
20:15
20:20
Time [mm:ss]

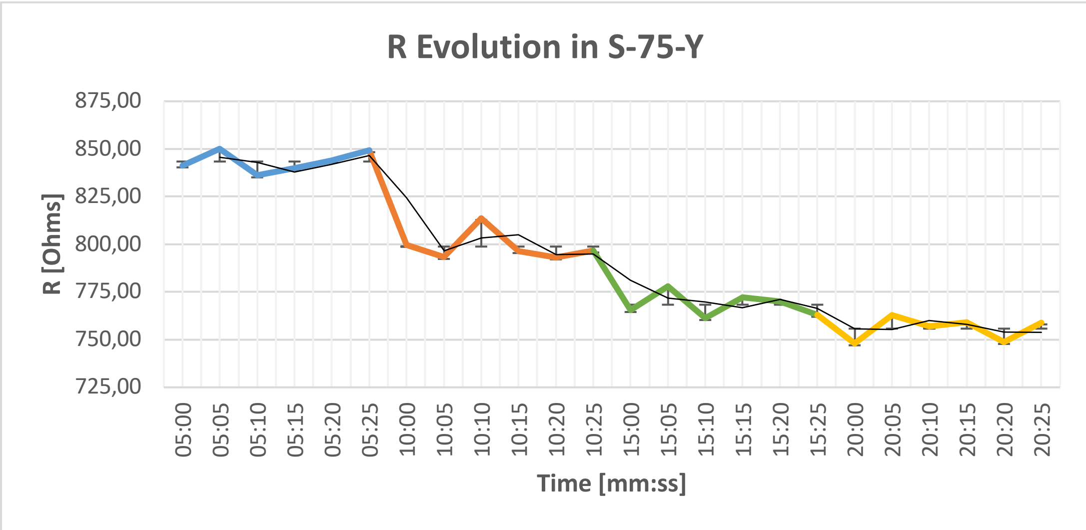

R Evolution in W-7-0,4-Y
R [Ohms]
825,00
800,00
775,00
750,00
725,00
05:00
05:05
05:10
05:15
05:20
05:25
10:00
10:05
10:10
10:15
10:20
10:25
15:00
15:05
15:10
15:15
15:20
15:25
20:00
20:05
20:10
20:15
20:20
20:25
Time [mm:ss]

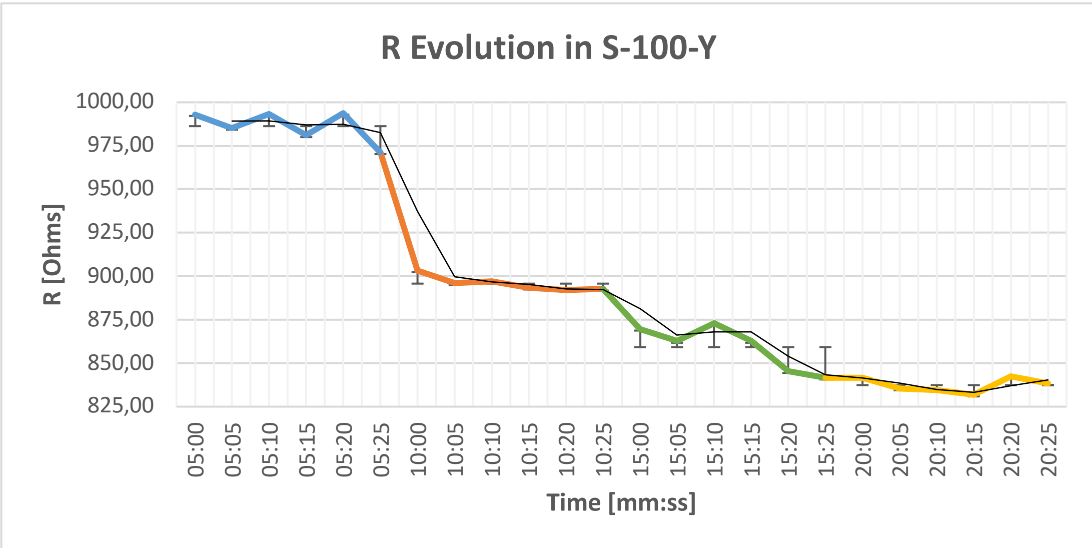

R Evolution in W-7-0,4-N
925,00
900,00
875,00
850,00
825,00
800,00
775,00
R [Ohms]
05:00
05:05
05:10
05:15
05:20
05:25
10:00
10:05
10:10
10:15
10:20
10:25
15:00
15:05
15:10
15:15
15:20
15:25
20:00
20:05
20:10
20:15
20:20
20:25
Time [mm:ss]

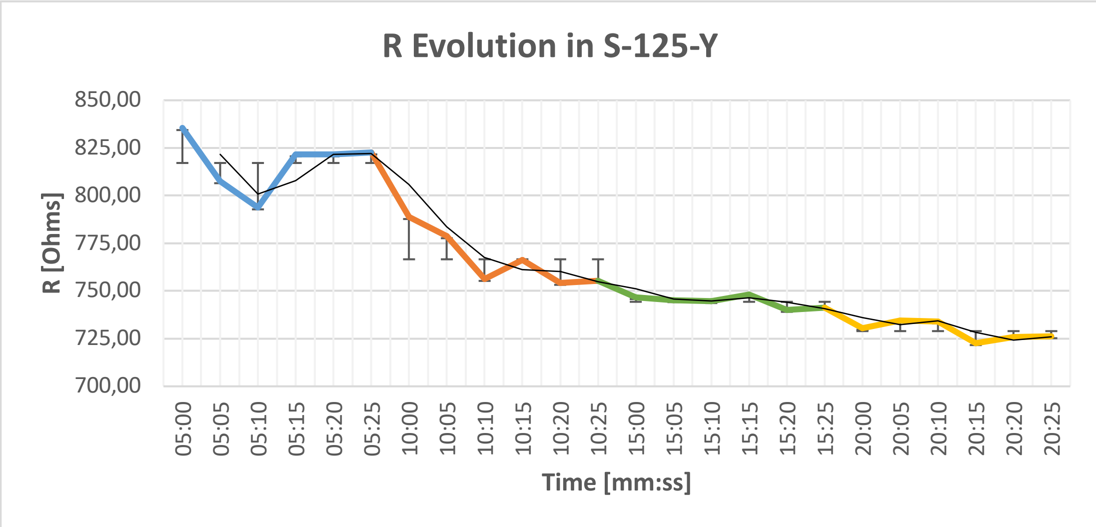

R Evolution in W-7-0,3-Y
775,00
750,00
725,00
700,00
675,00
650,00
625,00
R [Ohms]
05:00
05:05
05:10
05:15
05:20
05:25
10:00
10:05
10:10
10:15
10:20
10:25
15:00
15:05
15:10
15:15
15:20
15:25
20:00
20:05
20:10
20:15
20:20
20:25
Time [mm:ss]

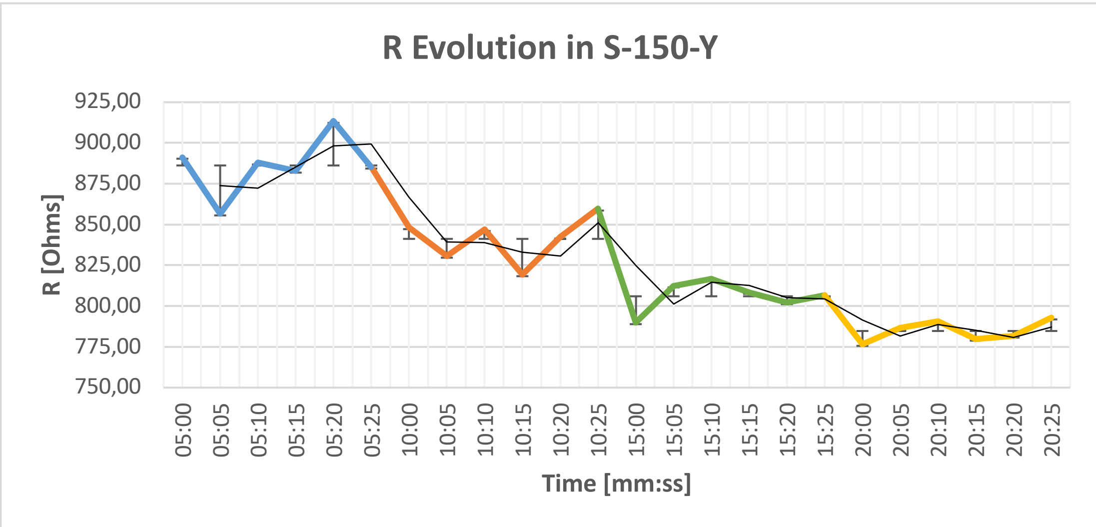

R Evolution in W-7-0,6-Y
R [Ohms]
800,00
775,00
750,00
725,00
700,00
675,00
650,00
05:00
05:05
05:10
05:15
05:20
05:25
10:00
10:05
10:10
10:15
10:20
10:25
15:00
15:05
15:10
15:15
15:20
15:25
20:00
20:05
20:10
20:15
20:20
20:25
Time [mm:ss]


R Evolution in S-50-Y
R [Ohms]
950,00
925,00
900,00
875,00
850,00
825,00
800,00
775,00
750,00
725,00
700,00
675,00
05:00
05:05
05:10
05:15
05:20
05:25
10:00
10:05
10:10
10:15
10:20
10:25
15:00
15:05
15:10
15:15
15:20
15:25
20:00
20:05
20:10
20:15
20:20
20:25
Time [mm:ss]


R Evolution in S-75-Y
875,00
850,00
825,00
800,00
775,00
750,00
725,00
R [Ohms]
05:00
05:05
05:10
05:15
05:20
05:25
10:00
10:05
10:10
10:15
10:20
10:25
15:00
15:05
15:10
15:15
15:20
15:25
20:00
20:05
20:10
20:15
20:20
20:25
Time [mm:ss]


R Evolution in S-100-Y
1000,00
975,00
950,00
925,00
900,00
875,00
850,00
825,00
R [Ohms]
05:00
05:05
05:10
05:15
05:20
05:25
10:00
10:05
10:10
10:15
10:20
10:25
15:00
15:05
15:10
15:15
15:20
15:25
20:00
20:05
20:10
20:15
20:20
20:25
Time [mm:ss]


R Evolution in S-125-Y
R [Ohms]
Time [mm:ss]
850,00
825,00
800,00
775,00
750,00
725,00
700,00
05:00
05:05
05:10
05:15
05:20
05:25
10:00
10:05
10:10
10:15
10:20
10:25
15:00
15:05
15:10
15:15
15:20
15:25
20:00
20:05
20:10
20:15
20:20
20:25


R Evolution in S-150-Y
R [Ohms]
Time [mm:ss]
925,00
900,00
875,00
850,00
825,00
800,00
775,00
750,00
05:00
05:05
05:10
05:15
05:20
05:25
10:00
10:05
10:10
10:15
10:20
10:25
15:00
15:05
15:10
15:15
15:20
15:25
20:00
20:05
20:10
20:15
20:20
20:25